SURFACE RUN-OFF BEHAVIOUR OF BITUMEN EMULSIONS USED FOR THE CONSTRUCTION OF SEALS

By

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Declaration

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Date: March 2013

Summary

'Simplicity is the ultimate sophistication' — Leonardo da Vinci

Factors influencing surface run-off of bitumen emulsions were studied in order to understand binders for use in the construction of surfacing seals.

Run-off of the binder from the road surface causes an inconsistent film thickness leading to ravelling (Johannes, Hanz & Bahia n.d.) and bleeding at the upstream and downstream regions, respectively.

There is currently no accepted specification for surface run-off viscosity. Practice mainly relies on empirical tests and experience. As the establishment of such a specification encompasses performance of the binder in various environments or field conditions, this study was undertaken to determine performance of the selected binder. Viscosity was kept constant by spraying the emulsion at a constant temperature and also holding the pavement temperature constant.

In order to study the run-off behaviour of the binder, run-off tests were conducted at various gradients, texture depths and spray rates. Surfacing seals of various texture depths were constructed in the laboratory. Using a spray bar, the emulsion was sprayed at various spray rates. The sample surfaces were tilted to various gradients.

Results portrayed the effects of the three factors (spray rate, gradient and texture depth) on the amount of runoff. An increase in the magnitude of the factors resulted in a variation in the runoff (increase or decrease). One notable finding was that the runoff from the 9.5 mm seal was less than that from the 13.2 mm seal. The other significant finding was that spray rate had the largest effect on runoff, followed by texture depth, and gradient.

Opsomming

Sekere eienskappe wat oppervlakdreinering van bitumen emulsies op paaie beinvloed, is bestudeer om sodoende binders wat gebruik word in die konstruksie van die seëls beter te verstaan.

Afloop van die binder vanaf die padoppervlak kan lei tot die vorming van 'n laag met ongelyke dikte wat moontlike rafeling (Johannes, Hanz & Bahia nd) en bloeing vanuit die onderkant van die pad tot gevolg kan hê.

Daar is tans geen aanvaarde spesifikasies wat hierdie verskynsels inperk nie. Konstruksie praktyk berus hoofsaaklik op empiriese toetse en ondervinding. Hierdie studie is dus onderneem om prestasie van die geselekteerde binder vas te stel. Viskositeit was konstant gehou deur die aangewende emulsie en padtemperatuur konstant te hou.

Ten einde die afloopgedrag van die binder te bestudeer, is toetse uitgevoer op verskeie hellings, tekstuurdieptes en aanwendingskoerse. Seëls van die verskillende tekstuurdieptes is gebou in die laboratorium, en emulsies op hierdie oppervlaktes aangewend. Die toetsoppervlakte is gekantel om die vereiste helling te kry.

Resultate vir die drie faktore wys die invloed op afloop. 'n Toename in die grootte van die faktore het gelei tot 'n variasie in die afloop (toename of afname). Een noemenswaardige bevinding was dat die afloop van die seël van 9,5 mm minder was as dié van die seël van 13,2 mm. Belangrike bevindinge sluit ook in dat die spuitkoers die grootste invloed het op afloop, gevolg deur die tekstuur diepte en die gradiënt.

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List of Abbreviations

AASHTO	American Association of State Highways and Transportation Officials
AC	Asphalt Concrete
ADOT	Arizona Department of Transport
ASTM	American Society for Testing and Materials
DSR	Dynamic Shear Rheometer
H	Height
HMA	Hot Mix Asphalt
MARC	Modified Asphalt Research Centre
PG	Performance grading
Q	Discharge
r	Correlation coefficient
RPM	Revolutions per minute
RV	Rotational Viscometer
SANRAL	South African National Roads Agency Ltd
SANS	South African National Standards
SF	Saybolt Furol
SHRP	Strategic Highways Research Program
SUPERPAVE	SUperior PERforming PAVEments
TG	Technical Guidelines
TMH	Technical Methods for Highways
TRH	Technical Recommendations for Highways
TxDOT	Texas Department of Transport

List of Units

%	Percent
cm	Centimeter
fpm	Feet per minute
ft	Foot/Feet
gal	Gallon
kg	Kilogram
km	Kilometer
kPa	Kilopascals
ℓ	Litre
ℓ/m^2	Litres per meter squared
ℓ/s	Litres per second
m	Meter
m/s	Meters per second
min	Minute
$m\ell$	Millilitre
$m\ell/m^2$	Millilitres per meter squared
mm	Millimeter
^{o}	Degrees
^oC	Degrees Celsius
^oF	Degrees Fahrenheit
Pa.s	Pascal second

s	Seconds
SFS	Saybolt Furol Seconds
sq yd	Square yard

Chapter 1 : Introduction

'The road to success is always under construction' — Lily Tomlin (but what is it paved with?)

1.1. Background to research topic

The field performance of bitumen[1] binders as a tack coat in spray seals depends on a number of factors. These include binder-related and environmental-related factors such as climate, topography and macro-texture of the existing surface. Environmental factors are fixed by nature and cannot be controlled. The binder's physical properties are, therefore, modulated in order to achieve satisfactory performance in particular environments.

The main physical properties of the binder include viscosity, stress, strain and ageing (Read & Whiteoak 2003; and Bahia, Jenkins & van de Ven 2011). These properties directly relate to the performance of the binder. The less important properties include: penetration, elastic recovery, ductility, force ductility, and toughness and tenacity. These are empirically tested and non-performance based (Bouldin & Dongre 2002).

All the above mentioned properties concern the rheology of the binder. Rheology is defined as the science of deformation and flow of matter. It encompasses elasticity, viscosity and plasticity (Webster's New World College Dictionary 2010). Rheology is important as it tells of the likely performance of the binder during construction and in-service. Run-off[2] is a construction performance parameter related to viscosity of the binder. Viscosity is the resistance to flow of a fluid[3] past a solid surface or other layers of the fluid due to internal friction of the fluid (Webster's New World College Dictionary 2010). During construction, viscosity is controlled such that the binder is sprayable, but not too fluid to run off the road surface. It is desired that the binder undergoes an immediate viscosity change just after spraying onto the road surface. The viscosity requirement during construction is, therefore, grouped under one parameter known as sprayability and run-off.

At spraying, the binder possesses a lower viscosity due to the high shear experienced at the nozzles of the spray bar (which breaks down the binder microstructure). When the binder

[1] The term "bitumen" is as also referred to as "the binder" in this document. Bitumen and its emulsions are used as binders in road surfacing.
[2] Surface run-off (verb) is also referred to as drain-out or drain-down in other literature (Bahia, Jenkins & Hanz 2008; and Bahia et al 2011). The word "run-off" as used in this document refers to both the verb and noun, and discretion should be made as to which figure of speech is referred to in relation to context.
[3] A fluid is defined as 'any substance that can flow; liquid or gas' (Webster's New World College Dictionary 2010).

reaches the pavement surface, a lower shear rate is experienced and hence its viscosity increases. This change in viscosity is experienced because the binder is thixotropic. Thixotropy is defined as a decrease in viscosity with time, under conditions of constant shearing (Brookfield Engineering Labs Inc. n.d.). Barnes (1997) defines thixotropy as a decrease of viscosity due to microstructure break down under constant shear stress or shear rate, followed by a gradual recovery of viscosity due to microstructure re-build when the stress or shear rate is removed. The time taken for the binder to rebuild its microstructure and attain a high viscosity at run-off is dependent on the viscosity at spraying.

1.2. Rationale

It is important to understand the run-off behaviour of binders so as to avoid pavement distresses resulting from loss of the binder or from inconsistent binder thickness after application. These distresses include ravelling and bleeding. By specifying the viscosity required to prevent run-off and that required for sprayability, unsatisfactory performance of the binder is eliminated. However, surface run-off is affected by other factors such as spray rate, gradient and texture depth. These factors were investigated in the present study.

This study shed light on how much binder is likely to run off the pavement surface given a specified spray rate. Using the chip seal design method provided in TRH3 (2007), for example, a spray rate is determined and it is verified that this falls within the recommended minimum and maximum values. In case it is noted that the spray rate chosen is higher than the limit specified for that particular binder, a more viscous binder (with a higher limit) is chosen. Rather than chose a more viscous binder, this study helps one weigh the likely benefits of using the less viscous binder in regard to cost and performance. This study is also helpful in linking viscosity to actual run-off.

It is confirmed from literature (Epps, Glover & Barcena 2001; Walubita, Epps-Martin & Glover 2005; Hoyt, Martin & Shuler 2010; and King et al. 2010) that the viscosity specification concerning sprayability and run-off of bitumen emulsions for the construction of surfacing seals is not yet established. This viscosity requirement is investigated by researchers at the Modified Asphalt Research Centre (MARC 2012), Wisconsin.

1.3. Problem statement

One of the specific gaps in factual knowledge of bitumen emulsion performance is surface run-off behaviour. This problem creates an opportunity to research surface run-off behaviour under laboratory conditions in order to find relationships between surface run-off and the most pertinent causative factors.

1.4. Research objective

The objective of this research is to determine the surface run-off behaviour of bitumen emulsion under varying conditions of spray rate, gradient and texture depth at constant viscosity. These are the most critical variable conditions identified in the field.

1.5. Scope and limitations of the study

This research is limited to unmodified cationic spray grade emulsion (65%), this being one of the two most commonly used types of bitumen emulsion for chip seals in South Africa. The other is modified cationic spray grade (70%). The latter was not considered because, from the researcher's experience, it does not usually run off easily.

Only three critical performance factors were considered, namely spray rate, gradient and surface texture depth. Other factors were not considered because these would make the project so big to handle. The latter also included the construction of three seal types to vary texture.

The binder was applied at one temperature (60°C) and the pavement temperature was held constant (at an ambient temperature of approximately 23-25°C). Only one binder temperature (60°C) was chosen as it is the recommended spray temperature in the field. This choice in temperature is further substantiated as the binder is sprayable even at 50°C and excessive heating is unnecessary. In practice, it is observed that the binder is sometimes sprayed at 50°C. Tests were conducted on pavements at ambient temperature. It would have been expedient to include a higher range of pavement temperatures. This, however, was not included in the scope of this research. Selecting one binder temperature kept viscosity at spraying as a constant in all tests.

1.6. Brief chapter overview

A literature review is provided in Chapter 2. Key topics included in this chapter are bitumen emulsions (general information), surfacing seals, performance grading and emulsion viscosity.

Chapter 3 details the research design and methodology that was used in this study. The processes that were followed and the experiments that were performed are described and justified.

The results of this research are presented and discussed in Chapter 4. Conclusions and recommendations are given in the final chapter, Chapter 5.

Chapter 2 : Literature review

'Some books are to be tasted, others to be swallowed, and some few to be chewed and digested' — Sir Francis Bacon.

2.1. Bitumen emulsions

2.1.1. Background to bitumen emulsions

Bitumen is 'a black viscous mixture of hydrocarbons obtained naturally or as a residue from petroleum distillation' (Oxford Dictionaries 2013). An emulsion is defined as a mixture of two or more immiscible liquids, with one liquid (the dispersed phase) dispersed in the other (the continuous phase) (North American Mixing Forum, NAMF n.d.). A bitumen emulsion is a mixture of bitumen and water, with an emulsifier added to ensure stability (Muller 2011). With bitumen emulsions, there are basically two scenarios:

i. The conventional bitumen emulsion, in which bitumen is dispersed in water in the form of discrete globules, typically 0.1 to 50 μm in diameter (Read & Whiteoak 2003). These emulsions are manufactured with various binder contents with 60%, 65% and 70% being the most popular; and
ii. The inverted emulsion, in which, water is dispersed in bitumen (Muller 2011).

Bitumen emulsions have been in use since the early 20th century (James n.d.b). Currently, approximately 9% of paving grade bitumen is used in emulsified form worldwide (Bahia et al 2011; and James n.d.b). Emulsion consumption, however, varies widely between countries (Bahia et al 2011; and James n.d.b).

The United States of America (USA) is the largest producer of bitumen emulsion in the world (James n.d.b). It is also the world's largest consumer of the same (2.6 million tons per annum), followed by France (1 million tons per annum) (Bahia et al 2011). Considering the total amount of bitumen consumed as emulsion compared to that consumed as plain bitumen within a country, France would be the largest consumer of bitumen emulsion in the world (Redelius 1994; and The Civil Engineering Contractor 2010). The proportion of roads constructed with emulsions compared to those constructed with plain bitumen is much higher in France than in the USA.

The bitumen emulsion consumption of South Africa is estimated at 80,000 tons per annum (The Civil Engineering Contractor 2010). The total road network in South Africa is approximately 754,000 km, of which over 70,000 km are paved (JAS forwarding SA (pty) Ltd 2012; and Brand South Africa n.d.). The USA, on the other hand, had a total road network of

6,506,204 km in 2008, of which 4,374,784 km were paved (CIA n.d.). A comparison of these figures shows that there is a large difference between the two countries for both paved and unpaved kilometres.

2.1.2. Advantages and disadvantages of using bitumen emulsion

Bitumen emulsions are more desirable than hot applied[4] and cut-back[5] binders because of the following reasons:

i. Environmental friendliness:
   a. Bitumen emulsions require much less energy during application, thereby reducing the amount of carbon dioxide and other greenhouse gases emitted (Muller, Sadler & Van Zyl n.d.; and Akzo Nobel n.d.b). They also require less energy during manufacture;
   b. These emulsions are safer to handle. No burns arise since there is little or no heat required before application (Muller, Sadler & Van Zyl n.d.; and Akzo Nobel n.d.b); and
   c. They have a low solvent content compared to cut-backs and therefore little or no contamination of the physical environment occurs (Muller, Sadler & Van Zyl n.d.; and James n.d.b)

ii. Practical considerations:
   a. There is no need to use dry, dust-free or pre-coated aggregate (Muller 2011);
   b. Bitumen emulsions have better adhesive properties, which is attributed to emulsification (Muller, Sadler & Van Zyl n.d.; and Muller 2011);
   c. Short-term ageing of the binder is avoided because heat is not required during storage and the binder is not heated to high temperatures during application (Muller 2011; and Bahia, Jenkins & van de Ven 2011);
   d. Bitumen emulsions are easy to apply and are therefore suited for application by intensive labour methods (especially slow set emulsions) (Muller, Sadler & Van Zyl n.d.);
   e. These emulsions provide an extended working time (during road construction) because they allow working at a minimum road surface temperature of $10^{o}C$. This results in increased production (Muller, Sadler & Van Zyl n.d.); and

[4] A hot applied binder refers to plain bitumen (modified or unmodified). This has to be heated to high temperatures greater than 100^{o} in order to reduce its viscosity so as to make it workable. Bitumen emulsions are taken to be warm/cold applied.

[5] A cut-back is bitumen to which a solvent has been added in order to reduce viscosity and make the bitumen workable. As for the case of bitumen emulsions, the application temperature of a cut-back is also lower than that of a hot applied binder.

f. ‘Bitumen emulsions are compatible with hydraulic binders like cement and lime as well as water-based polymer dispersions like natural and synthetic latex. When mixtures of cement, latex, and bitumen emulsion cure, a composite binder is produced with a structure that cannot be duplicated with hot applied bitumen and with significantly improved properties compared to plain bitumen’ (James n.d.b, p.2).

iii. Better factor of safety:

a. Bitumen emulsions provide a more flexible transverse distribution, even with blocked nozzles, compared to the more viscous hot applied binder that would produce evident streaks (Muller, Sadler & Van Zyl n.d.);
b. These emulsions allow for additional binder to be applied with ease (allow lower application rates) (Muller, Sadler & Van Zyl n.d.); and
c. Construction is easily performed, with less rolling required (Muller, Sadler & Van Zyl n.d.)

Bitumen emulsions also have some setbacks. Muller (2011) highlights the following disadvantages to the use of these emulsions:

i. The emulsion can be washed away easily by the rain during the curing period;
ii. Modified emulsion may have a false break, whereby only the top of the layer breaks and forms a coating, and this traps water within the layer. This results in the emulsion taking longer to set (Muller 2011; and Muller, Sadler & Van Zyl, n.d.);
iii. The formulation of emulsions needs to take into account aggregate type, mineralogy, reactivity and charge; and
iv. Bitumen emulsions are more likely to run off the pavement surface compared to hot applied binders.

There has been some advances in emulsion technology, notably in the setting process, as detailed below:

i. Breaking agents may be used to provide accelerated curing (James n.d.b);
ii. Wetting agents may be used to allow quicker removal of water and hence earlier bonding of the coalesced bitumen with the mineral surface (James n.d.b); and
iii. The cohesion of the binder can be monitored as the emulsion cures, allowing quicker opening to traffic (Construction Review Online 2009).

Due to the advantages offered by bitumen emulsions compared to cut-backs and hot applied bitumen, emulsion usage is likely to increase in the near future. Research into the improved performance of bitumen emulsions is required if emulsions are to outcompete plain bitumen.

2.1.3. Possible structures of bitumen emulsions

There are three possible structures of bitumen emulsions, as described by Esfeh, Ghanavati & Arani (2010), Akzo Nobel (n.d.b), and James (n.d.b):

i. **Oil-in-water (O/W) emulsions**: 'O/W emulsions are those in which the continuous phase is water and the dispersed phase is a water-insoluble "oily" liquid' (Esfeh, Ghanavati & Arani 2010, p.55; Akzo Nobel n.d.b, p.3; and James n.d.b, p.2). Conventional binders are usually considered to be of the O/W type and contain 40-75% bitumen, 0.1- 2.5% emulsifier, and 25- 60% water (James n.d.b).

ii. **Water-in-oil (W/O) emulsions:** 'W/O emulsions are those in which the continuous phase is an oil and the dispersed phase water' (Esfeh, Ghanavati & Arani 2010, p.55; Akzo Nobel n.d.b, [p.3]; and James n.d.b, p.2). W/O emulsions are referred to as "inverted emulsions" (Esfeh, Ghanavati & Arani 2010; Akzo Nobel n.d.b; and James n.d.b). These emulsions are based on cut-back bitumens (Akzo Nobel n.d.b).

iii. **Multiple phase (W/O/W) emulsions:** in multiple phase emulsions, the dispersed oil droplets contain smaller droplets of water or another liquid of a composition different from the continuous phase (Esfeh, Ghanavati & Arani 2010; and James n.d.b).

The above three emulsion structures are illustrated in Figure 2.1 below.

Oil-in-water emulsion **Water-in-oil emulsion** **Multiple emulsion**

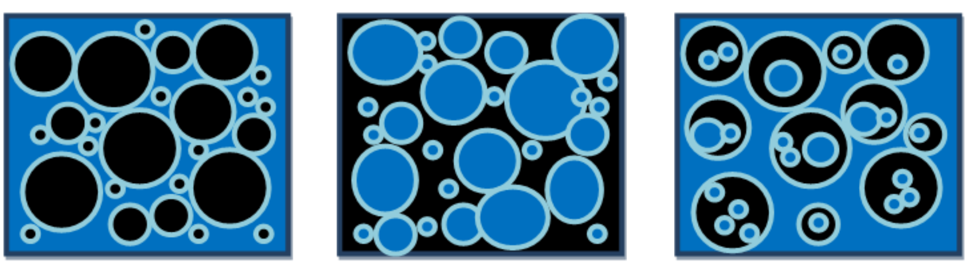


Figure 2.1: Emulsion structures

Bitumen emulsions are better described by a W/O/W multiple structure because some bitumen particles may contain small water droplets within them. The viscosity of the emulsion and in particular the changes in viscosity of the emulsion during storage are strongly influenced by this internal water phase (James n.d.b; and Esfeh, Ghanavati & Arani 2010).

2.1.4. Types of bitumen emulsions

Bitumen emulsions are classified according to the type of surfactant/emulsifier used to make the emulsion. Emulsifiers are usually supplied in a water-insoluble form and are therefore reacted with an acid or alkali to make them water soluble (Read & Whiteoak 2003; and James n.d.b). Five types of bitumen emulsions, namely (i) anionic, (ii) cationic, (iii) non-ionic, (iv) clay-stabilized and (v) amphoteric emulsions, are described in more detail below.

i. Anionic emulsions

Anionic emulsions are made with fatty acids that have been saponified (an ester heated with an alkali) with sodium, ammonium or potassium hydroxide (Morgan & Mulder 1995; and Akzo Noble n.d.b), as follows:

R-COOH + NaOH → $R\text{-}COO^- Na^+$ + H_2O (Morgan & Mulder 1995)

(Fatty acid) (Base) (Anionic soap) (Water)

R in the above and proceeding chemical structures represents the hydrophobic part of the emulsifier and is normally composed of a hydrocarbon chain consisting of 8-22 carbon atoms originating from natural fats and oils (Read & Whiteoak 2003). Read & Whiteoak (2003) state that the hydrophilic head groups could contain amines, sulphonates, carboxylates, ether or alcohol groups.

On dissociation in water, the soap molecule splits into $R\text{-}COO^-$ and Na^+ ions. The $RCOO^-$ attaches itself to the bitumen droplet, imparting a negative charge to it. Anionic emulsions have a pH range of 7–14 and are used with neutral or positively charged aggregates (Muller 2011).

ii. Cationic emulsions

Cationic emulsifiers are made by dissolving amines, diamines or amino alkoxylated amines in hydrochloric, acetic, phosphoric or sulphuric acid (Morgan & Mulder 1995; and Akzo Noble n.d.b), as shown below. The reaction is carried out by carefully controlling pH, producing amine salts (Morgan & Mulder 1995).

$R\text{-}NH_2$ + HCl → $R\text{-}NH_3^+ Cl^-$ (Morgan & Mulder 1995; James n.d.b; and Akzo Noble nd.b)

(Amine) (Hydrochloric acid) (Alkylammonium chloride – cationic soap)

On dissociation, the molecule splits to form R-NH_3^+ and Cl^- ions (Muller 2011). The RNH_3^+ attaches itself to the bitumen droplet, imparting a positive charge to it. Cationic emulsions have a pH range of 1-7 and are used with neutral or negatively charged aggregates (Muller 2011). Cationic emulsions are most commonly used in road construction because these emulsions have good adhesion with most types of mineral aggregate (TG2 2009; and Bahia, Jenkins & van de Ven 2011).

iii. Non-ionic emulsions

Non-ionic emulsions are formed by non-ionic emulsifiers. These emulsifiers are covalent, polar, dissolve without ionisation and have the following chemical structure: R-$COO(CH_2CH_2O)_xH$ (Read & Whiteoak 2003).

Non-ionic emulsifiers are considered to have a neutral (i.e. non-ionic) charge. The charge on the bitumen emulsion droplet, if any, is obtained from ionic species in the bitumen itself (Read & Whiteoak 2003). Wate and James (n.d.) found that non-ionic emulsifiers produce emulsions that are negatively charged and thus anionic. This negative charge is, however, small (James n.d.b).

As non-ionic emulsifiers have got no charge, bitumen droplets are prevented from coming into contact with each other by the size of the emulsifier head (Suleiman 2006). This is referred to as steric hindrance (Suleiman 2006). Read & Whiteoak (2003) state that non-ionic emulsifiers are not produced in large quantities and are usually only used to modify anionic and cationic emulsions used in the production of slow-setting bitumen emulsions (James n.d.b). The most commonly used non-ionic emulsifiers include nonylphenolethoxylates and ethoxylated fatty acids (Read & Whiteoak 2003).

iv. Clay-stabilised emulsions

Read & Whiteoak (2003) state that in clay-stabilised emulsions, fine powders such as clay and bentonites are used for emulsifiers. The powder provides mechanical protection around the bitumen particles, and this, together with the thixotropic structure of the emulsion, hinders movement of the bitumen particles, thereby preventing agglomeration (Read & Whiteoak 2003). Clay stabilised emulsions are used for industrial applications, such as roofing, and not for road construction (Read & Whiteoak 2003).

v. Amphoteric emulsions

Akzo Noble (n.d.b) and James (n.d.b) note that there are also amphoteric emulsifiers. Amphoteric emulsifiers have both anionic and cationic head groups. The emulsifier is either positively or negatively charged depending on the pH (Shrivastava et al n.d.). The term “amphoteric” is defined as ‘having the characteristics of an acid and a base and capable of reacting chemically either as an acid or a base’ (American Heritage Dictionary 2010).

Although emulsifiers may be classified as anionic (negatively charged), cationic (positively charged) or non-ionic (neutral) based on the charge their head groups adopt in water, the emulsifier charge may also depend on pH (James n.d.b; and Esfeh, Ghanavati & Arani 2010). Some cationic emulsifiers could have a neutral head group charge at a pH of 11, and similarly some anionic emulsifiers would be neutral at a pH of 2 (James n.d.b). The dosage of the acid or base during emulsifier production determines the final pH of the emulsion.

2.1.5. Grades of bitumen emulsion

Bitumen emulsions are also graded by the rate of set (or break) into the following four categories: (i) spray grade/rapid set (ii) pre-mix grade/medium set (iii) stable grade/slow set and (iv) quick setting. Each of these is discussed below.

i. Spray Grade/Rapid Set (RS)

Spray grade emulsions set quickly when in contact with clean chip stones such as those used to construct surface dressings (Akzo Nobel n.d.b; and James n.d.b). This would be approximately 1-5 minutes for unmodified emulsions (Asphalt Emulsion Manufacturer’s Association n.d. cited in Raza 1994). Spray grade emulsions are reactive and are therefore used with unreactive aggregates (aggregates of low surface area) (James n.d.b). These emulsions are not used in aggregate mixes (Asphalt Institute 2008).

ii. Pre-mix Grade/Medium Set (MS)

Pre-mix grade emulsions take some time to set (at least 30 minutes) and are also used with aggregates of low surface area (Akzo Nobel n.d.b; James n.d.b; and Raza 1994). These emulsions are formulated such that they can mix with aggregate and are therefore sometimes called mixing grade emulsions (Asphalt Institute 2008). The Asphalt Institute & AEMA (2008) state that mixes made with pre-mix grade emulsions can remain workable from a few minutes to several months depending upon the formulation. Pre-mix grade emulsions are used in open-graded mixes (James n.d.b), dense-graded mixes (cold and warm), cold recycling and patch mixes (Asphalt Institute 2008).

iii. Stable Grade/Slow Set (SS).

Stable grade emulsions are unreactive and therefore take a few months to set. These emulsions are used with reactive aggregates of high surface area (Akzo Nobel n.d.b; and James n.d.b, p.4). 'Aggregate reactivity is mostly associated with the very finest-size fractions which make the highest contribution to surface area' (James n.d.b, p.5). The common applications of stable grade emulsions are found in slurry seals, dense-graded aggregate bases, asphalt surface courses, soil stabilisation and some recycling (Asphalt Institute 2008; and Asphalt Institute & AEMA).

iv. Quick Setting (QS) emulsions

Quick setting emulsions are those with an intermediary reactivity between medium set and slow set, and which do not need to pass the cement mix test (James n.d.b). These emulsions are designed mainly for slurry seals and micro-surfacing (Asphalt Institute & AEMA). The type of emulsion used in rapid setting slurry or micro-surfacing is a polymer modified cationic quick setting emulsion (Raza 1994; and TRH3 2007) or a modified emulsion with rapid curing characteristics (TRH3 2007).

James (n.d.b) states that setting rate not only depends on the reactivity of the emulsion and the reactivity of the aggregate reactivity (aggregate fineness), but also on environmental factors such as temperature, wind speed, humidity and mechanical action from the roller/compactor.

2.1.6. Nomenclature of bitumen emulsion

The American and South African systems of naming bitumen emulsions are described below.

i. The American system

The following codes in Table 2.1 on the next page are used in the American system to denote the various types of emulsions.

Table 2.1: American designation of bitumen emulsions (James n.d.b)

Property	Description	Code
Setting rate	Cationic Rapid Set	CRS
	Cationic Medium Set	CMS
	Cationic Slow Set	CSS
	Cationic Quick Setting	CQS
	Anionic Rapid Set	RS
	Anionic Medium Set	MS
	Anionic Slow Set	SS
	Anionic Quick Setting	QS
Emulsion viscosity	1	Low viscosity
	2	High viscosity
Residue properties	H	Hard asphalt residue (hard bitumen residue)
	S	Soft asphalt residue (soft bitumen residue)
	HF	High Float
Other naming schemes from local authorities:		
Modification	P or LM	Polymer-modified or latex-modified
Solvent content	S	High solvent content
Emulsions with specific uses	AEP	Asphalt emulsion prime (Bitumen emulsion prime)
	PEP	Penetrating emulsion prime
	ERA	Recycling agent emulsion

The following are a few examples of the use of the above nomenclature (James n.d.b; and Asphalt Institute 2008):

a) CRS-2P: A polymer modified cationic rapid setting emulsion of high viscosity;
b) SS-1H: A slow-setting anionic emulsion of low viscosity and a hard bitumen residue;
c) HFMS-1: A high float medium set emulsion; and
d) HFRS-1P: A high float polymer modified rapid set emulsion.

The Asphalt Institute (2008) notes that High Float emulsions are manufactured so that the emulsifier forms a gel structure in the bitumen residue. This gel structure results in a thicker bitumen film that allows the emulsion to perform effectively in a wider temperature range (Asphalt Institute 2008). The resulting thickness also prevents runoff of the binder from the surface of the road. High Float emulsions are not only used in chip seals, but also in cold mixes (Asphalt Institute 2008).

ii. The South African system

Emulsions are categorised as cationic spray grade, pre-mix grade or stable grade; or anionic spray grade, pre-mix grade or stable grade without codes. The binder content is then specified. In terms of binder content, a 60% binder content is equivalent to the viscosity designation 1 in the American system (see Table 2.1 above), and a 65% and 70% binder content is equivalent to designation 2 (Louw 2012).

South Africa uses a unique nomenclature for modified emulsions. According to TG 1 (2007), the modified binder classification follows the following criteria:

- *The type of application in which they are intended to be used*
  - *Seal (S)*
  - *Asphalt (A)*
  - *Crack sealant (C)*
- *The type of binder system*
  - *Emulsion (colder applied) - If the product is an emulsion then the letter C would follow directly after the letter indicating the type of application.*
  - *Hot applied – No letter is used after the letter indicating the type of application.*
- *The predominant type of modifier used*
  - *Elastomer (E) e.g. A-E1*
  - *Plastomer (P) e.g. A-P1*
  - *Rubber (R) e.g. A-R1*
  - *Hydrocarbon (H) e.g. A-H1*
- *The level of modification*

  A higher numerical number represents a higher softening point value but this does not necessarily imply improved overall performance properties. It is only meant to enable higher order modified binders be included in the classification framework in future should the need arise by increasing the numerical value.
- *Whether or not the use of a fluxing agent or cutter is permitted*

If the binder application does not permit the use of flux or cutter, the letter "t" should be shown in brackets after the classification.

As an example, a classification of SC-E2(t) indicates that the binder is:
S - intended to be used for a surfacing chip seal
C - it is an emulsion
E - the main modifier is an elastomer
2 - it has a higher softening point than an SC-E1
(t) - the use of a fluxing agent or cutter is prohibited

Other examples include:
AC-E1: Microsurfacing- emulsion elastomer modified
CC-E1: Crack sealant-emulsion elastomer modified
(modified from TG 1 2007, p.26 & 27).

2.1.7. Typical applications of various grades of bitumen emulsion

The choice of emulsion to be used for a particular application depends on aggregate reactivity, emulsion reactivity and environmental conditions, as previously mentioned in Section 2.1.5.

Aggregate reactivity is associated with the amount of fines contained in a mix blend, or on the surface of large sized aggregates (dusty aggregates) in the case of chip stones used in chip seals. Finer aggregates have a higher surface area providing greater attraction to the bitumen droplets in the emulsion. As a result, finer aggregates would cause the emulsion to break faster than coarser aggregates.

Bitumen reactivity is associated with the amount of emulsifier or the strength of the charge on the bitumen droplet. A stronger charge is associated with greater attraction of the droplet to an aggregate of the opposite charge.

James (n.d.b) summarises the common applications of various grades of bitumen emulsion (see Table 2.2 on the next page). The Asphalt Institute & AEMA (2008) also provide applications for specific types of emulsion (see Table 2.3 on page 16).

Table 2. 2: Typical applications of bitumen emulsions (James n.d.b)

	Anionic			Cationic		
	RS	**MS**	**SS**	**RS**	**MS**	**SS**
Plant Mixes						
Open-graded		✓[a]			✓[a]	
Dense-graded			✓			✓
Reclaimed asphalt pavement (RAP)		✓				✓
Stockpile mix		✓[a]			✓[a]	
Pre-coated chips					✓	✓
Mix Paving						
Open-graded					✓[a]	
Slurry			✓			✓[b]
Slurry for capeseal			✓			✓[b]
Microsurfacing						✓[b]
In-Place Mixes						
RAP		✓[a]			✓[a]	✓
Dense-graded			✓			✓
Soil stabilization			✓			✓
Spray Applications						
Chipseal	✓			✓		
Fog seal–cement curing		✓		✓	✓	
Tack coat		✓[a]	✓		✓[a]	✓
Prime			✓[a]			✓[a]
Dust palliative			✓			✓
Mulch			✓			
Penetration macadam				✓		
Other						
Waterproofing coatings			✓[c]			
Driveway and footpath sealers			✓[c]			✓[c]

[a] -May contain solvent

[b] -Need not pass cement test

[c] -May contain clay

Table 2. 3: General uses of bitumen emulsions (adapted from Asphalt Institute & AEMA 2008)

Type of constructions	ASTM D977, AASHTO M208									ASTM D2397, AASHTO M140						
	RS-1	RS-2	HFRS-2, HFRS-2h	MS-1, HRMS-1	MS-2, HFMS-2	MS-2h, HFMS-2h	HFMS-2s	SS	SS-1h	CRS-1	CRS-2, CRS-2h	CMS-2	CMS-2h	CSS-1	CSS-1h	CQS-1h
Bitumen aggregate mixtures:																
Plant mix (warm)[A]					X	X						X	X			
Plant mix (cold)																
Open-graded aggregate					X	X						X	X			
Dense-graded aggregate						X	X	X	X					X	X	
Sand						X	X	X	X					X	X	
Mixed-in-place:																
Open-graded aggregate				X	X	X						X	X			
Well-graded aggregate						X	X	X	X					X	X	
Sand						X	X	X	X					X	X	
Sandy soil						X	X	X	X					X	X	
Bitumen-aggregate applications:																
Single & multiple chip seals	X	X	X								X					
Sand seal	X	X	X	X						X	X					
Slurry seal									X						X	X
Micro-surfacing																X^E
Sandwich sand seal		X	X								X					
Cape seal		X	X						X		X				X	X
Bitumen applications:																
Fog seal	X			X^B				X^C	X^C	X					X^C	X^C
Prime coat					X^D			X^D	X^D					X	X^D	X^D
Tack coat	X			X^B				X^C	X^C	X					X^C	X^C
Dust palliative	X^B							X^C	X^C	X^B				X^C	X^C	X^C
Crack filler								X	X					X	X	
Maintenance mix:																
Immediate use					X	X	X					X	X			
Stockpile					X		X					X				

[A]Other grades may be used if experience has shown that satisfactory performance has been obtained
[B]Diluted with water by manufacturer
[C]Diluted with water
[D]Mixed-in prime only
[E]Polymer must be added during or prior to emulsification

2.1.8. Bitumen emulsion manufacture

Manolis (2010) states that bitumen emulsions are composed of the following constituents:

i. Bitumen (asphalt cement), 40-70%;
ii. Water (usually soft water), 30-50%;
iii. Emulsifier (also referred to as a surfactant or a soap), 0.3-2.5%;
iv. Solvent (at times), 0-30%;
v. Polymers (at times), 0-4%; and
vi. Other additives (such as magic dust), 0-1%

The emulsifier is usually mixed with the desired proportion of water that is to be added to the bitumen, forming what is called a soap solution (James n.d.b). Hot bitumen (in a temperature range of 100-140^{o}C, viscosity not exceeding 0.2 Pa.s) and the soap solution are then fed separately but simultaneously into a colloid mill (Read & Whiteoak 2003) as illustrated in Figures 2.2 and 2.3. The temperature of the water/soap solution is adjusted so that temperature of the exiting emulsion is less than 90^{o}C (Read & Whiteoak 2003).

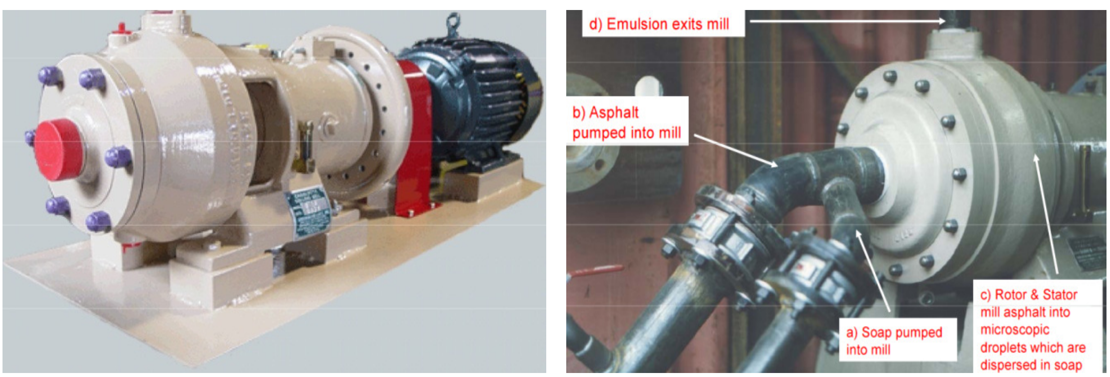


Figure 2. 2: Colloid bitumen emulsion mill (Manolis 2010)

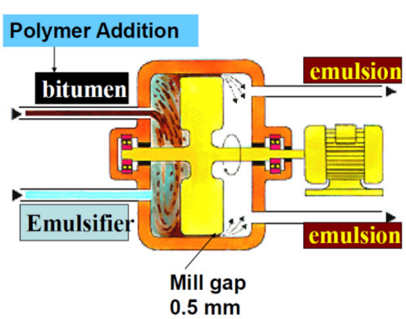


Figure 2.3: Cross section through colloidal mill (Bahia et al 2011)

As described by Read & Whiteoak (2003), the mill consists of a rotor which revolves between 1000 and 6000 RPM in a stator. This provides a strong mechanical force that shears the bitumen into small droplets. The gap between the rotor and stator is normally adjusted between 0.25-0.50 mm (Read & Whiteoak 2003) depending on the median size of bitumen droplets desired (Manolis 2010).

An alternative to the colloidal mill is a static mixer, that is, a mixer with no moving parts (Shrivastava et al n.d.; and Read & Whiteoak 2003).

A low viscosity (maximum viscosity limit of 0.2 Pa.s) is used because it is desired that the hydrocarbon binder thoroughly disperses in the aqueous phase (James n.d.b). This viscosity is obtained by keeping the binder at a temperature appropriate to its penetration factor (Roffe 2008). Approximate values are given in Table 2.4 below.

Table 2. 4: Emulsification temperatures for various bitumen penetration values (Roffe 2008)

Bitumen pen	Emulsification temperature (°C)
160/220	140
70/100	150
50/70	160

'As the bitumen and emulsifier solution enter the colloid mill, they are subjected to intense shearing forces that cause the bitumen to fragment into small globules' (Read & Whiteoak 2003, p.97). The emulsifier coats each individual globule, giving an electrical charge to the surface of the droplets. The resulting electrostatic force inhibits coalescence of the globules (Read & Whiteoak 2003).

2.1.9. Emulsion production processes

Bitumen emulsions can be manufactured using the batch or continuous (in-line) process plant. Each of these processes is described in more detail below. The continuous plant produces larger volumes of emulsions compared to the batch plant (Read & Whiteoak 2003).

i. The batch manufacturing process

This process is illustrated in Figure 2.4 on the next page. Akzo Nobel (n.d.b) states that two main process steps are involved, namely soap preparation and the actual emulsion production. In the soap preparation step, the emulsifier and other chemicals are batched into a measured quantity of heated water and the solution mixed thoroughly. In the emulsion production step, the bitumen and the pre-made soap are dosed to the colloid mill. If solvent is to be added to the bitumen, this may done in a bitumen batch tank or dosed in-line (Akzo Nobel n.d.b)

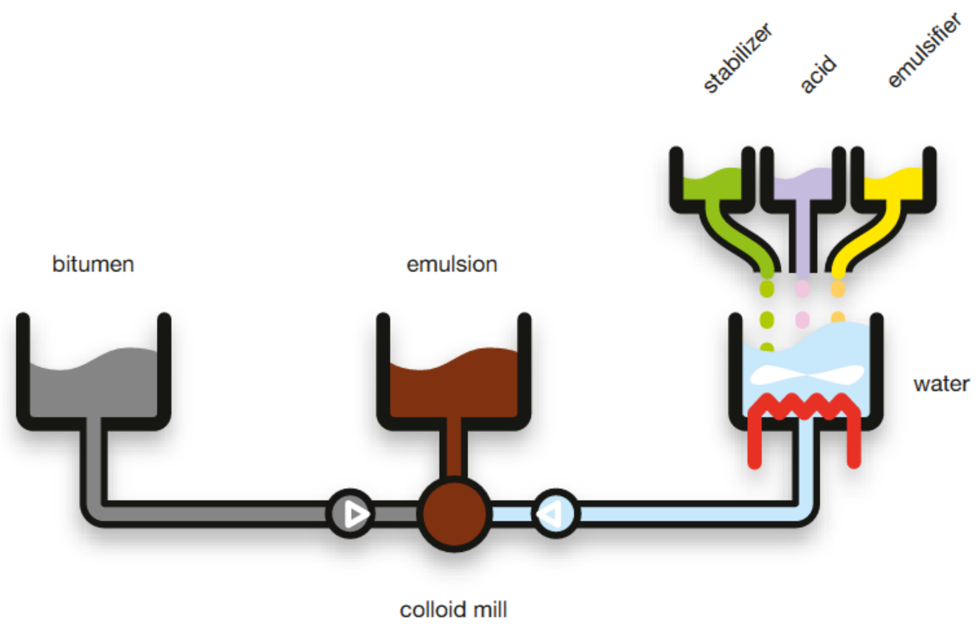


Figure 2.4: The batch emulsion production process (Akzo Noble n.d.b)

ii. The continuous manufacturing process

In the continuous production process, heated water and all other materials are dosed in-line, continuously using individual dosage pumps for each material (see Figure 2.5). The soap system is, however, allowed sufficient time in order for the chemicals to react, neutralise and form a solution before the soap meets the bitumen (Akzo Nobel n.d.b).

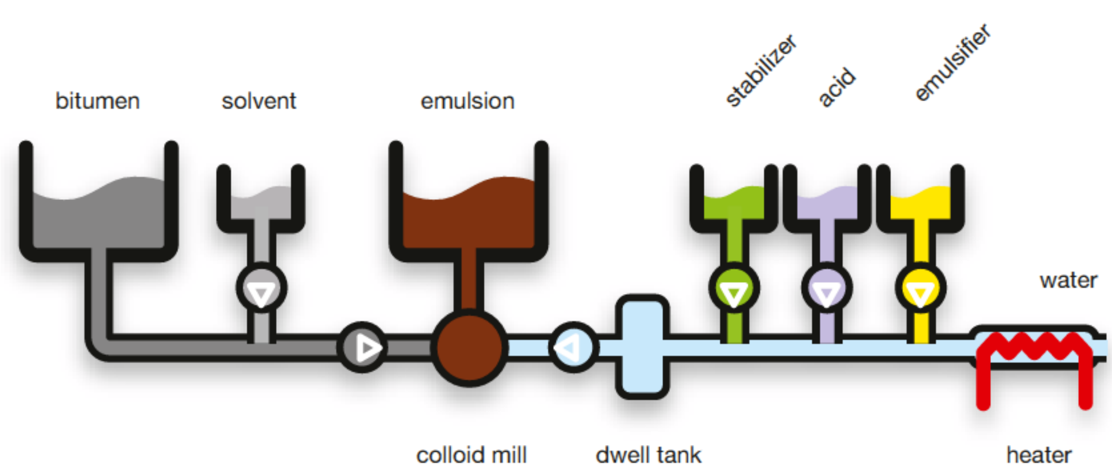


Figure 2.5: Continuous emulsion production process (Akzo Noble n.d.b)

iii. Semi-continuous emulsion production process

Manolis (2010) describes the semi-continuous production process as consisting of two soap tanks, one in use and the other on standby (see Figure 2.6). A switch is made to the new soap when the first batch runs out, such that the mill runs continuously (Manolis 2010).

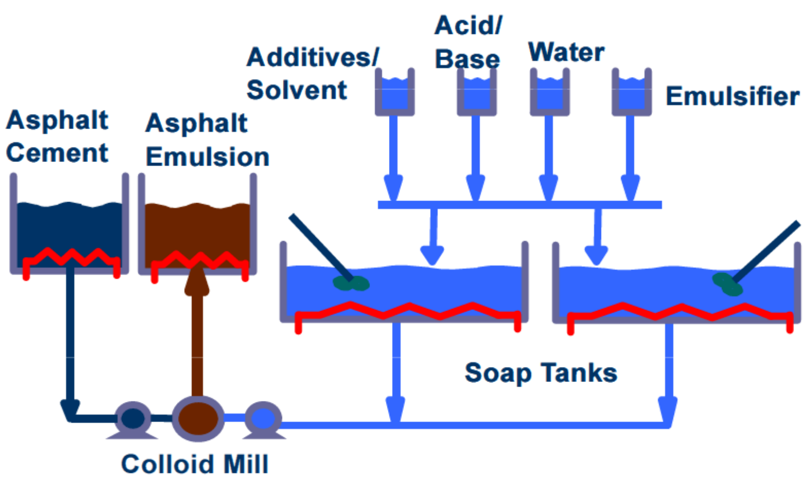


Figure 2.6: Semi-continuous emulsion production process (Manolis 2010)

The author proposes that the solvent not be placed at the location indicated in Figure 2.6, but in a separate bitumen batch tank, as previously mentioned. Water and the solvent, for example diesel are immiscible, with diesel being lighter. When the two are mixed in the presence of an emulsifier, the emulsifier would attach itself to the solvent rather than being reserved for the bitumen. The solvent would then not be able to dissolve the bitumen with the emulsifier around it. From observation, when a solvent is added after the emulsion has been produced, flocculation and coagulation are delayed.

During production, regardless of the type of manufacturing process used, the temperature of the outgoing emulsion can be predicted using the following equation:

$$Emulsion\ temp\ (\,^{o}F) = \frac{[(AC\ wt\%)\times(AC\ temp)\times 0.5]+[(Soap\ wt\%)\times(Soap\ temp)]}{[(AC\ wt\%)\times 0.5]+[Soap\ wt\%]}$$ (Manolis 2010).

Where $AC\ wt\%$ = asphalt cement proportion, and

$Soap\ wt\%$ = soap proportion.

Temperatures are in ^{o}F.

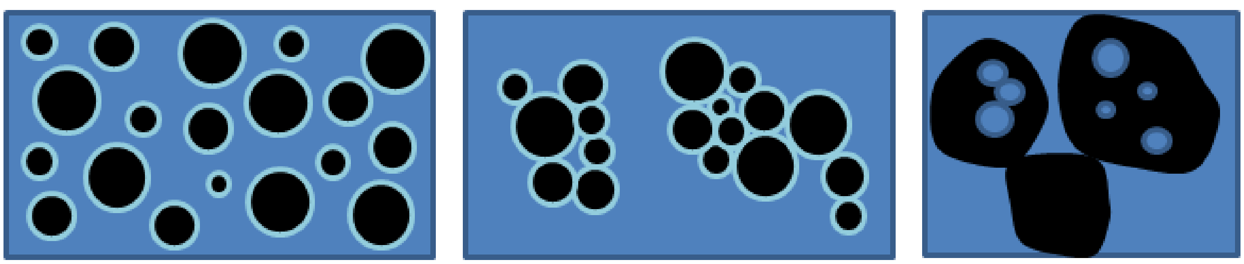
2.1.10. Kinetic stability of emulsions

Emulsions are kept stable using an emulsifier. The emulsifier is divided into a hydrophilic and hydrophobic part. When the emulsifier is mixed with bitumen in the colloid mill, it orientates itself such that the hydrophobic part attaches to the bitumen droplet. The hydrophilic part is charged (for charged emulsifiers), and provides an electrical and steric repulsion[6] energy barrier, which helps prevent the droplets from coming into close contact with each other (Akzo Nobel n.d.b). Akzo Nobel (n.d.b) states that even if this energy barrier is overcome and the droplets flocculate, coalescence would still be inhibited by the film of emulsifier on the surface. This is true for stable emulsions in which gentle agitation restores the droplet dispersion within the continuous phase. For unstable emulsions, flocculation immediately results in coalescence (ScanRoad n.d).

Akzo Nobel (n.d.b) further states that "free" emulsifier (emulsifier in excess of that required to fill the interface) helps to prevent coalescence during emulsification, storage and transport.

The various stages of stability are shown in Figure 2.7 below.

Stable emulsion | **Flocculation** | **Coalescence**



Close approach is prevented by the charge on the droplets.

Adhesion between droplets occurs as a result of the close approach.

Electrical and steric repulsion energy barrier is overcome. Spherical droplets deform and fuse. Water drains between the droplets.

Figure 2.7: Stability of emulsions (Akzo Nobel n.d.b)

When stored in drums, the emulsion needs to be agitated every two weeks (Holleran 2009b) by rolling the drum on its side or by stirring using a rod. This re-suspends the bitumen drops that could have settled, thereby prolonging the shelf life of the emulsion. When stored in bulk

[6] Steric repulsion is the repulsion created when an atom intrudes into the space of the electrons of an another atom (Shusterman 2009)

tanks, the emulsion needs to be circulated once a week in summer and every five days in winter, for most emulsions (Holleran 2009b).

Since laminar flow is experienced as the bitumen droplets settle (Reynolds number less than 0.1), the motion of these droplets is described by Stokes' Law. Stokes' Law is a mathematical expression that describes of the drag force exerted on a spherical body as it moves through a quiescent, viscous fluid at specific velocity (Hudson n.d.). It is given by $F_d = 6\pi r\eta V$, where

F_d = drag force of the fluid on the sphere (N)

η = viscosity (Pa.s);

V = velocity of the sphere relative to the fluid (m/s); and

r = radius of the sphere (m)

A spherical body moving through a fluid experiences three forces as shown in Figure 2.8. These include the weight, mg, buoyancy force, F_b and the drag force F_d. If the weight of the sphere is greater than the buoyancy and drag force, the sphere will accelerate downwards. Stokes' Law helps to predict the settling velocity of the sphere.

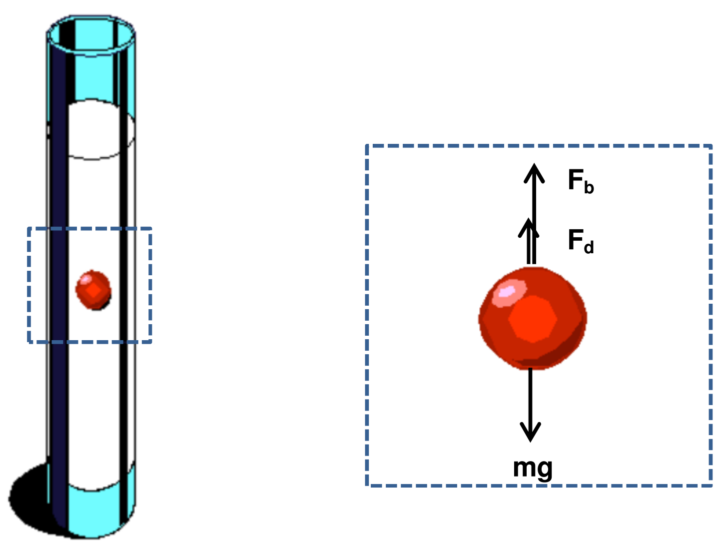


Figure 2.8: Forces acting on a sphere in a quiescent fluid (Hudson n.d.)

2.1.11. Emulsion storage temperatures

The shelf life of an emulsion is not only dependent on formulation (emulsion composition) but also on storage temperature. Emulsions are usually stored between 10-85^{o}C depending on emulsion type and intended use (The Heritage Research Group 2008). It is not recommended that the emulsion be heated above 85^{o}C because at elevated temperatures, water evaporates changing the characteristics of the bitumen emulsion. Low temperatures, on the other hand, cause the emulsion to freeze and break, separating the bitumen from water (The Heritage Research Group 2008). The Asphalt Institute & AEMA (2008), The Heritage Research Group (2008), and Redman (2012) give a summary of the minimum and maximum temperatures for various grades of bitumen emulsion (see Tables 2.5 and 2.6, respectively).

Table 2.5: Storage temperatures for bitumen emulsions (adapted from Asphalt Institute & AEMA 2008)

Emulsion grade	Minimum temperature (^{o}C)	Maximum temperature (^{o}C)
CQS-1h, QS-1h, Micro-surfacing emulsion	10	50
RS-2, CRS-1, CRS-2, HFRS-2, CMS-2, CMS-2h, MS-2, MS-2h, HFMS-2, HFMS-2h	50	85
RS-1, SS-1, SS-1h, CSS-1,CSS-1h, MS-1	10	60

Table 2.6: Recommended storage temperatures for bitumen emulsions (The Heritage Research Group 2008; and Redman 2010)

Emulsion grade	Minimum (^{0}C)	Maximum (^{0}C)
RS-1	21.1	60
RS-2, CRS-2, CRS-2P, HFRS-2, AE-90, MS-2	51.7	85
SS-1h, CQS-1h, CSS-1hM	10	60

Other literature gives the above values in Tables 2.5 and 2.6 as emulsion application temperatures (Transportation Information Centre 1992). This is also supported by The Heritage Research Group (2008).

2.2. Chip seals (surfacing seals)

2.2.1. Brief introduction

A surfacing seal is essentially a thin film of bituminous binder sprayed onto the road surface and covered with a layer of aggregate, which could be stone or sand. The aggregate is placed immediately after binder application, and compacted immediately to ensure close contact and thus good adhesion between the chip stones and the binder film (TRH3 2007).

The purpose of a surfacing seal, as for any other type of wearing course, is to provide a durable, waterproof, skid-resistant and all weather dust-free surfacing, and to protect the structural layers of the pavement from abrasive forces of traffic as well as from the effects of the environment (TRH3 2007).

Seals are used for new construction as well as maintenance treatments for example patching, crack sealing, edge break repair, correction of roughness, rut filling and texture treatment (Van Zyl n.d.). Gransberg & James (2005) state that chip seals are effective in sealing non-structural cracks. According to these authors, even though chip sealing is viewed as a means of preventing further deterioration while awaiting rehabilitation funds, this sealing should not be used on badly cracked or weathered surfaces. Such use would be more expensive in the long run as chip seals are not expected to provide additional structural capacity to the pavement (Gransberg & James 2005).

TRH3 (2007) also states that most seals are relatively thin and have no load distribution properties. They are used satisfactorily only for pavements whose underlying layers (base, subbase and subgrade) have adequate structural capacity to sustain traffic loads (TRH3 2007). Nevertheless, seals should be able to accommodate horizontal and vertical traffic-induced stresses (TRH3 2007).

Chip seals are also used as stress absorbing membrane interlayers (SAMI) between the old surfacing and the new asphalt overlay (Hoffmann & Potgieter 2007). As a SAMI, the chip seal prevents cracks from the old surfacing from reflecting through the asphalt overlay and also acts as a waterproof cover to the underlying pavement (Hoffmann & Potgieter 2007).

2.2.2. Use of chip seals as wearing course

TRH3 (2007) states that surfacing seals carry from approximately 125 to 20,000 equivalent light vehicles (elv) per lane per day. Though there are some surfacing seals that have performed well under much greater traffic (up to 60,000 elv per lane per day), it is usually recommended that an asphalt surfacing be used for heavier volumes of traffic (TRH3 2007).

From the 2003 road network classification, 80% of surfaced road in South Africa are sealed (TRH3 2007; and Distin 2008a). Seals are desirable because of their favourable cost compared to other surfacing types (Distin 2008a). However, seals last for 10 to 15 years, a shorter period compared to HMA's design life of 20 to 25 years (CD Paving and seal coating n.d). According to Gransberg & James (2005), chip seals are expected to last at least for 5 years and therefore resurfacing would be required three to four times during the pavement's design life. The life expectancy of surfacing seals as provided in TRH3 (2007) varies from 3-14 years (for new construction) depending on traffic, seal type and whether a modified binder is used or not.

2.2.3. Types of surfacing seals

There are various types of surfacing seals, but the most commonly used include the following, illustrated in Figure 2.9 below.

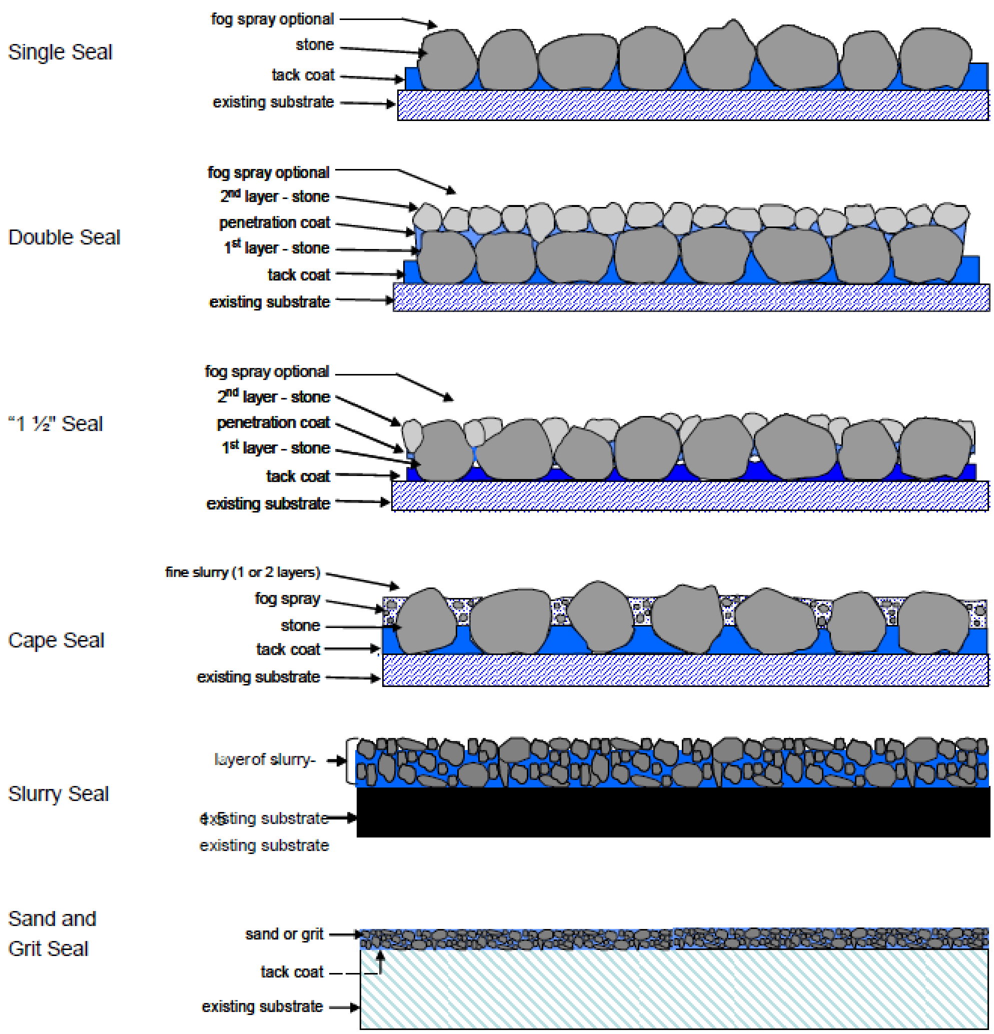


Figure 2.9: Schematic illustration of seal types (TRH3 2007)

The less commonly used seals are shown in Figure 2.10 on the next page.

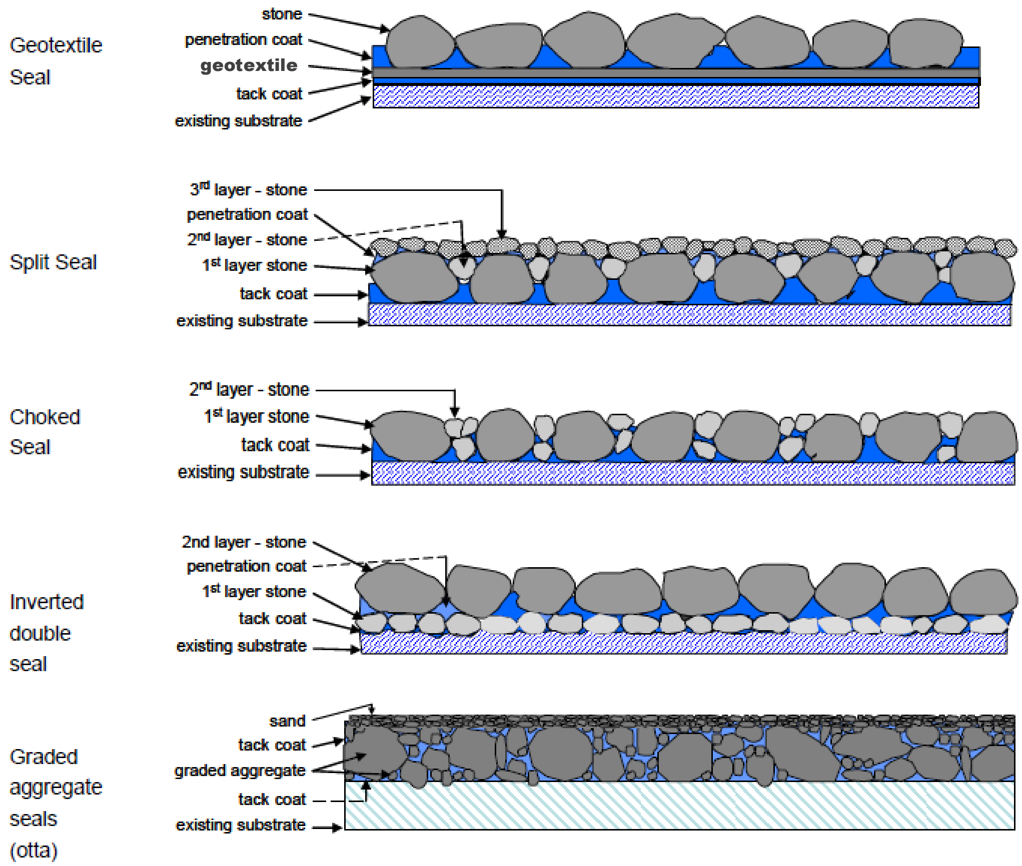


Figure 2.10: Schematic illustration of seal types (TRH3 2007)

The choice of seal type for initial surfacing can be made using Tables 4-1 to 4-4 in TRH3 (2007).

2.2.4. Binders used with surfacing seals

Various types of binders, ranging from conventional to polymer modified binders, are used in the construction of chip seals. These are shown in Figure 2.11 on the next page. As of 2008, it was estimated that more than 40% of all sprayed binders used in surfacing seals in South Africa were modified (Distin 2008a). This increased use of modified binders over the previous ten years was attributed to increased traffic on rural roads. Distin (2008a) also noted that industry preferred the use of hot binders rather than emulsion or cutback bitumen as the former favoured higher sealing production rates.

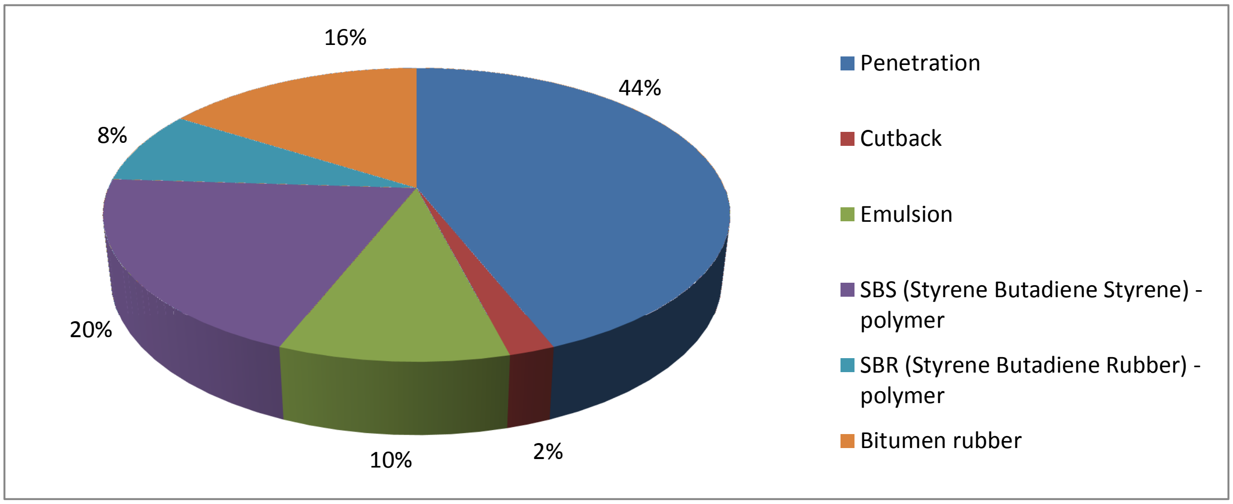


Figure 2.11: Usage of different types of binders in spray seals in South Africa (Distin 2008a)

2.2.5. Factors influencing the performance of surfacing seals

TRH3 (2007) discusses the various factors that influence the performance of surface seals. These include the following:

i. **Pavement structure and condition:** The performance of a seal depends on the structural capacity of the pavement layers underneath, as highlighted below:
   a. A pavement structure that cannot resist high deflections would cause the pavement layers and the surfacing seal to fatigue;
   b. Base material unable to resist penetration of aggregate into the layer would cause fatting, bleeding and skidding problems being experienced with the seal; and
   c. Reflective cracks appear in the surface dressing if the underlying base has active cracks (movement between the crack walls caused by load repetitions, chemical reactions which cause shrinkage, temperature changes and changes in moisture conditions) (TRH3 2007).

ii. **Existing substrate:** The following conditions of the underlying surface determine the choice of seal type, the type and quantity of binder required, the size of stone used and the necessary pre-treatment:
   a. *Surface texture depth:* An additional binder would be required owing to surface texture and the need for texture pretreatment;
   b. *Permeability:* An additional binder would be needed for pretreatment to seal voids;

c. *Expected aggregate embedment*: This gives an indication of how much voids in the seal would be lost due to embedment. The amount of voids in the aggregate matrix determine whether the seal would bleed or not; and
d. *The degree and extent of cracking:* Seal work could be planned so that it incorporates correction of brittle existing surfaces that show cracks. Surfacing seals would not be used as a remedial measure for heavy structural cracks, as these would reflect through the new surfacing seal with time (TRH3 2007).

iii. **Traffic:** The following traffic parameters affect seal performance:

a. *Traffic Volume:* On the one hand, traffic volume, particularly of heavy vehicles, significantly affects embedment, wearing and polishing of the stone. On the other hand, the seal is hypothetically required to handle a minimum number of vehicles per day to keep the binder alive and flexible. This would be approximately 50 vehicles per day for conventional binders and a greater number for modified binders (TRH3 2007). The kneading action of traffic continuously brings fresh binder to the surface of the binder layer (not surface of the wearing course) and the exposed and oxidised binder to the inside;
b. *Loading:* A high rate of embedment is caused by heavy axle loads compared to light axle loads;
c. *Tyre pressure*: The amount of bleeding is increased by the existence of high tyre inflation pressures, synonymous to loading in (b) above. TRH3 (2007, p.11) reports that 'Heavy Vehicle Simulator tests showed that there was a significant increase in flushing[7] on sections trafficked with similar wheel loads but with higher inflation pressures'. It is also important to note that if the tyre pressure is too low in relation to the load, the sidewalls of the tyre carry all the load and this results in high contact pressure too (Molenaar 2007);
d. *Vehicle types and characteristics:* The turning action of tandem and tridem axles causes shoving and ravelling;
e. *Speed:* Vehicles at a speed of less than 40km/h cause the pavement surface to experience longer loading time, higher horizontal stresses as a result of braking and accelerating, and exposure to oil/fuel spillage, which aggravates flushing and deformation. Fast-moving vehicles would be an advantage (TRH3 2007, p.11); and
f. *Traffic distribution:* Traffic concentration within wheel tracks rather than its distribution within the lane width causes the wheel tracks to become fatty and in-between the wheel tracks to be brittle, and may cause edge breaks. The

[7] Flushing is another word for bleeding or fattiness

period of traffic occurrence during the life of the seal, for example before the seal has cured or at cold temperature when the binder is brittle, also significantly affects the performance of the seal (TRH3 2007).

iv. **Road geometry:** Some geometrical factors that contribute to poor performance of seals include the following:
   a. *Gradients:* Steep gradients pose a construction difficulty and hence the risk of poor seal performance. In addition, traction forces of vehicle tyres cause debonding, slippage of the surface and flushing. Canalized water flow down steep slopes can cause erosion of chip stones;
   b. *Curves*: Navigation of sharp corners requires a reduction in speed for a smooth transition and, as a result, high horizontal stresses are generated. These high stresses cause ravelling and slippage of the surface. On low trafficked roads, vehicles also usually prefer to travel on the inner side of the curve. This results in the outer part of the curve becoming dry and brittle and the inner part fatty;
   c. *Intersections*: Intersections experience slow speed, leading to the effects mentioned in (iii)(e); and
   d. *Road width*: This influences traffic distribution, the effects of which are highlighted in (iii)(f) (TRH3 2007).

v. **Design:** A thorough site investigation is required by the designer in order to obtain the latest information on the condition of the road and also to make provisions for anticipated or likely scenarios in design (TRH3 2007).

vi. **Materials:** The characteristics of the aggregate and the binder play a role in the performance of the seal, as explained below:
   a. *Aggregate:* The following aggregate-linked factors influence seal performance (TRH3 2007):
      i. Aggregate shape, size and grading: These factors affect interlock, stability and the void content of the seal. The bigger the void content, the greater the ability of the aggregate to accommodate variation in binder application rate without flushing. More binder can also be used with larger aggregate, resulting in a more impermeable, longer lasting seal;
      ii. Aggregate spread rate: A very low spread rate of aggregate may cause excessive ultraviolet damage to the binder and ravelling of the seal, whereas a very high spread rate forces excessive aggregate into the mat, leading to whip-off of bonded aggregate;

iii. Adhesion characteristics: Adhesion between aggregate and binder is negatively influenced by the presence of dust and moisture on the aggregate, except if emulsions are used. Such aggregate may be pre-coated to avoid adhesion problems.

iv. Strength, durability and wearing characteristics: Quality aggregate is required to avoid failure in crushing, weathering or polishing under traffic; and

v. Porosity: Porous aggregate absorb lighter fractions of the bitumen and should therefore be pre-coated before use or a modified binder should be selected (TRH3 2007).

b. *Binder:* The following binder-related factors influence seal performance (TRH3 2007):

i. Binder type and properties: Modified binders are preferred to conventional binders (penetration grade, cut-back and emulsion) due to the former displaying improved adhesion, elasticity, lower sensitivity to bleeding and higher durability;

ii. Binder grade: penetration grade bitumen, cut-backs and bitumen emulsion each have a unique grading/classification system. For penetration grade bitumen, each grade has a corresponding application viscosity that should be observed for best workability and unification on laying. For bitumen emulsions, the compatibility of a cationic or an anionic emulsion with aggregate determines whether the two will have an excellent bond or not. Furthermore, the climatic condition at the time of binder application may necessitate the use of cutters or binder modification; and

iii. Binder application rate: <u>The application rate should be such that the predetermined amount of binder is achieved and is uniformly distributed, with special consideration to the possibility of run off on steep slopes</u> (TRH3 2007) (my underlining).

vii. **Preparation, pre-treatment and repairs before construction:** Surface preparation is important to remove dust, which can affect the binder bond with the surface. Inadequate preparation can result in scabbing, this defined as the detachment of both the binder and chip stones from the existing road surface after application (Kerman et al 1999). Pre-treatment and repairs are required for evening out surface irregularities and defects that would reflect through or cause debonding of the seal. Repairs should be scheduled well before construction of the seal, so that the treatments are given time to stabilise and hence minimise the embedment of aggregate (TRH3 2007).

viii. **Construction supervision:** Effective supervision eliminates poor construction practices and pays attention to detail which could affect the performance of the seal (TRH3 2007).

ix. **Maintenance:** Timely maintenance extensively lengthens the life the seal and the pavement structure as a whole (TRH3 2007). Preventive maintenance such as the application of a fog spray is highly beneficial.

x. **Physical and social environment:** This includes the following six factors:

   a. *Climatic conditions:* 'Temperature and precipitation (rainfall) are recognised as the main factors to be considered in selection of binders for seals. Temperature can have direct impact on wetting, fattiness, early ravelling, and fatigue. High temperatures can enhance wetting, encourage breaking, and reduce ravelling, but could negatively impact fattiness. Conversely, lower temperatures could result in reduced wetting, slow breaking, and more ravelling or fatigue. Lower temperatures could also reduce fattening. Rainfall and humidity also affect wetting' (Bahia, Jenkins and Hanz 2008, p.5);

   b. Drainage systems: Single seals, thin sand seals and slurry seals are susceptible to erosion and are therefore not recommended on steep gradients with urban type drainage (TRH3 2007);

   c. *Mechanical damage:* Damage caused by agricultural machinery using the road or rims of flat tyres result in rapid deterioration of the surfacing if not corrected in time;

   d. *Dust or wind-blown sand:* This causes adhesion failure for freshly applied binder;

   e. *Organic matter:* Organic matter such as animal droppings, sugar cane and the presence of salt water or detergent negatively affect durability of the seal; and

   f. Developing areas: The temporary use of streets for the storage of building materials in developing urban areas damages the seal (TRH3 2007).

The above factors can be summarised into five groups of related factors, namely:

i. Existing pavement condition, which encompasses layer strength/stiffness, surface suitability to receive tack coat, and the need for pre-treatment and repairs;

ii. Traffic and geometry. This includes traffic volume, axle loads, tyre pressure, vehicle types and characteristics, vehicle speed, traffic distribution and occurrence, steep gradients and the navigation of sharp corners, all of which are interrelated by stress induced in the pavement.

iii. Design, supervision and maintenance, the combination of which ensures a structurally sound and durable construction;
iv. Materials, including the size and grading of aggregate, spread rate of aggregate, binder application rate, aggregate cleanliness, aggregate selection, and binder selection. The performance and durability of the seal depends on the proper design and construction/handling of materials; and
v. Physical and social environment. This also determines the suitability of the binder and how quickly it deteriorates.

2.3. Performance grading

In order to produce pavements that performed well in service, the Strategic Highways Research Program (SHRP) developed SUPERPAVE (SUperior PERforming PAVEments) binder specifications to limit binder contribution to the dominant distresses experienced by HMA pavements (Read & Whiteoak 2003). These SUPERPAVE binder specifications are aimed at controlling various physical properties of the binder, such as viscosity, stiffness and strain, in different environmental conditions (this being in regard to climate, traffic volume, traffic speed, pavement structure and ageing of bitumen); and hence categorising binders into grades based on their performance characteristics (Read & Whiteoak 2003).

Previously, the penetration (Pen), viscosity (AC) and Aged Residue (AR) grading systems were used, but these were found to be limited in the ability to fully characterise bitumen binders for use in HMA pavements (Pavement Interactive 2008). Some limitations of these systems are addressed by the SUPERPAVE PG system are provided in Table 2.7 below.

Table 2.7: Prior limitations versus SUPERPAVE testing and specification features (adapted from Roberts et al 1996 cited in Pavement Interactive 2008)

Limitations of penetration, AC and AR grading systems	SUPERPAVE binder testing and specification features that address prior limitations
Penetration and ductility tests are empirical and not directly related to HMA pavement performance.	The physical properties measured are directly related to field performance by engineering principles
Tests are conducted at one standard temperature without regard to the climate in which the binder will be used.	Test criteria remain constant; however, the temperature at which the criteria must be met changes in consideration of the binder grade selected for the prevalent climatic

	conditions.
The range of pavement temperatures at any one site is not adequately covered. For example, there is no test method for binder stiffness at low temperatures to control thermal cracking.	The entire range of pavement temperatures experienced at a particular site is covered.
Test methods only consider short-term binder ageing (thin film oven test), although long-term ageing is a significant factor in fatigue cracking and low temperature cracking.	Three critical binder ages are simulated and tested, namely: 1. The original binder prior to mixing with aggregate; 2. The aged binder after HMA production and construction; and 3. The long-term aged binder.
Binders can have significantly different characteristics within the same grading category.	Grading is more precise and there is less overlap between grades.
Modified binders are not suited for these grading systems.	Tests and specifications are intended for all types of bitumen, i.e. conventional and modified bitumen binders.

Though the SUPERPAVE PG grading system overcomes the above mentioned limitations, it is being improved because of the some setbacks. A few of these setbacks, as found in HMA application, include:

i. Grade bumping, to account for heavy traffic and slower speeds. It is assumed that increasing the test temperature by 6^{o}C and holding the criteria value constant will basically double the stiffness of the binder. This leads to testing at temperatures far above the temperature where the stresses and strains will occur, leading to erroneous results that do not correlate to the performance (D'Angelo n.d.);

ii. SUPERPAVE specifications are unable to differentiate between the performance of conventional blown or chemically treated binders, from polymer modified binders of the same grading. This has led to the use of SHRP+ specifications and empirical non-performance based tests such as elastic recovery, ductility, force ductility and toughness & tenacity. Users would like to identify the type of modification, as elastometric modifiers have an excellent field performance history compared to plastomeric modifiers (Bouldin and Dongre n.d.); and

iii. Testing is done in the linear viscoelastic range, which does not capture the mixture fatigue performance (Bahia, Wen & Johnson n.d.) and the response to rutting (D'Angelo n.d.).

The SUPERPAVE performance grading specifications were, however, specifically designed for HMA and are not suitable for seals. This is because chip seals differ from HMA in terms of construction methods, structural functions, behavioural responses, distress types and environmental exposure (Hoyt, Martin & Shuler 2010).

2.3.1. Properties that determine seal performance and are related to the binder

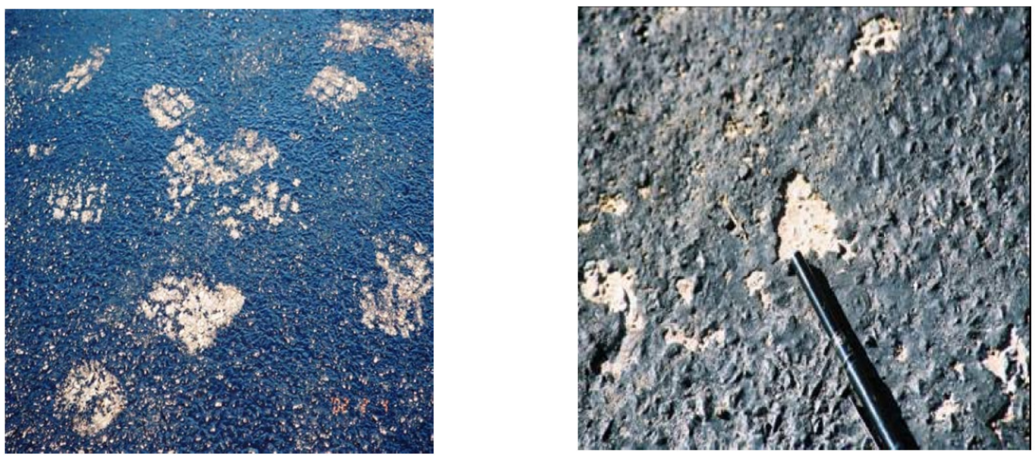
Bahia, Jenkins and Hanz (2008) highlight the following construction-related and in-service related properties tested to evaluate the performance of binders used in surfacing seals:

i. **Construction related properties:**

a. *Storage stability:* Storage stability is the ability of bitumen droplets to stay dispersed throughout the continuous phase. Depending on the density of the bitumen phase compared that of the continuous phase, the bitumen droplets could either settle to the bottom of the storage tank or rise to the top (creaming) (ScanRoad n.d.). For a stable emulsion, gentle agitation restores its original quality after settlement, but this is not possible with unstable emulsions. The settlement in the latter results in coalescence and breaking of the emulsion, making the emulsion unusable (ScanRoad n.d.). Settlement can be prevented by keeping the emulsion at higher than ambient temperature (ScanRoad n.d.). Factors that influence settlement are droplet size, the density of the bitumen phase, the viscosity of the water phase (presence of a thickening agent), the amount of emulsifier and storage temperature (ScanRoad n.d.);

b. *Sprayability and run-off:* Sprayed bitumen must have a viscosity such that it will form an even fan and laterally distribute on the pavement. The viscosity should also be such that 'the bitumen must not run off the pavement and must form an even membrane on which to apply the chip stones [thixotropy]' (Holleran 2009a). Viscosity is influenced by bitumen content, the temperature of the emulsion, droplet size distribution, the type and dosage of emulsifier and stabiliser, the salt content and viscosity of the bitumen (ScanRoad n.d.). Runoff is also influenced by the spray rate and shear thinning hysteresis loop (Holleran 2009a);

c. *Breaking and setting rate:* This is the time it takes for the emulsion to be transformed to a bitumen film after it has been sprayed. The process involves destabilisation and flocculation of the bitumen particles (a rapid process called breaking), and the coalescence of floccules and evaporation of water from the continuous bitumen film (a slower process called setting) (Redelius & Walter 2006 cited in Hanz, Arega and Bahia 2008b). 'The rate of breaking should allow for proper binder distribution, spread of aggregates, and rolling of the aggregates in binder film' (Hanz, Arega and Bahia 2008b, p.3). An example of failure caused by a slow breaking emulsion (Figure 2.12a) and by a fast breaking emulsion (Figure 2.12b) is shown below.



a) b)

Figure 2.12: 'Construction related failures: a) Slow breaking and tacky emulsion, prone to pick-up and b) Fast breaking emulsion lacking penetration' (photographs adapted from van Zyl n.d. cited in Bahia, Jenkins and Hanz 2008)

The breaking and setting rate is influenced by the type and dosage of emulsifier, as the amount of emulsifier affects stability and breaking; the type of aggregate, as breaking may not occur if the aggregate is of similar charge to that of the emulsifier; climate, with a hot and windy climate favouring faster setting; and mechanical effects, such as rolling with a compactor (Hanz, Arega and Bahia 2008b). The breaking and setting rate also determines when the pavement can be opened to traffic.

d. *Wetting of aggregates/wettability:* Wettability is the ability of bitumen to wet the aggregate surface, and is dependent on the surface energy of the bitumen and aggregate. Surface energy across an interface (solid-liquid, liquid-gas or solid-gas interface) or the surface tension at the interface is defined by NDT Resource Center (n.d.) as a measure of the energy required to form a unit area of new surface at the interface.

Contact angle is an indication of the potential wettability of a surface. The contact angle is defined as the angle formed by the solid/liquid interface measured from the side of the liquid (NDT Resource Center n.d.) (see Figure 2.13 below). A lower contact angle is associated with increased wettability.

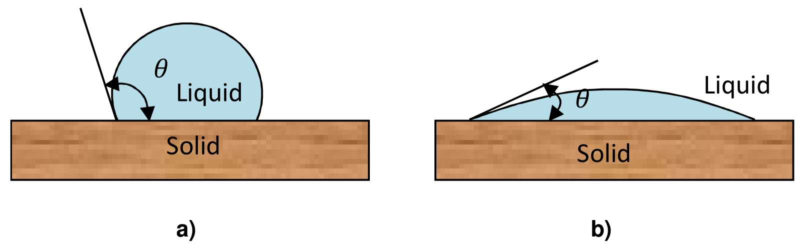


Figure 2.13: Contact angle: a) low wettability and b) high wettability (adapted from NDT Resource Center n.d.)

If the bitumen (emulsion) molecules have a stronger attraction to each other than to the surface of the aggregate, the bitumen beads-up and does not wet the aggregate surface (NDT Resource Center n.d.).

Bahia, Jenkins and Hanz (2008) state that aggregate has a higher affinity to water than bitumen and therefore would have a tendency to form bonds with water rather than bitumen as the emulsion breaks and cures.

Appropriate selection of 'surfactant can remedy this issue by displacing the water from the aggregate surface hence allowing strong aggregate-bitumen adhesive bonds to develop' (Hanz, Arega and Bahia 2008, p.9). The magnitude of adhesion is an important consideration in resisting ravelling.

Wetting can also be enhanced by adding a cutter[8], usually in amounts of 0-5% by mass of bitumen, into spray grade emulsions (Bahia, Jenkins and Hanz 2008).

e. *Tackiness (Hanz, Arega and Bahia 2008a):* This refers to the stickiness of bitumen and is related to cohesion being affected by moisture. Tacky emulsions are prone to pick up, as indicated in Figure 2.12a on page 35.

[8] A cutter is a volatile solvent added to bitumen to temporarily reduce its viscosity. An example is paraffin.

ii. In-service related properties:

a. *Resistance to ravelling:* This refers to the loss of surface aggregate from a completed surface dressing (Kerman et al 1999) due to oxidation of the binder (an aged binder that is too stiff and brittle) or caused by moisture affecting the adhesion/cohesion bond;

b. *Resistance to thermal cracking:* As the pavement temperature drops, the binder contracts and builds up internal stresses. If the binder does not have enough time to relax these stresses, the latter accumulate to a critical point at which cracking occurs (Pavement Interactive 2011). Thermal cracking is worsened if low temperature is combined with ageing, resulting in a much stiffer binder that is more difficult to relax;

c. *Resistance to fatigue cracking:* Repeated loading from heavy traffic induces tensile stresses above the tensile strength of the bitumen, leading to crack propagation and failure. Fatigue may also be caused by underlying weak pavement layers that deflect (TRH3 2007); and

d. *Resistance to bleeding/fattiness:* Bleeding occurs when bitumen is exuded from the road surface by the action of heavy traffic (Gransberg & James 2005). It is caused by 'excess binder in proportion to the aggregate or where the aggregate is forced to achieve levels of embedment beyond the design embedment depth' and is accelerated by high temperatures (Gransberg & James 2005, p.58). Kerman et al (1999) state that bleeding often extends beyond wheel tracks and is caused by low binder viscosity, high pavement temperatures, excess binder and stripping of the binder as a result of water pressure. These authors define fattiness as a surface layer of free bitumen caused by an almost total embedment of aggregate. Fattiness usually occurs only in the wheel tracks (Kerman et al 1999).

Of the in-service related types of failure mentioned above, the most important and dominant failure modes are: fattiness, ravelling and fatigue cracking (Bahia, Jenkins & Hanz 2008). Epps, Glover & Barcena (2001) and Walubita, Epps-Martin & Glover (2005), however, state that the principle mode of distress for surface treatments is aggregate loss due to flow and brittle fracture at high and low temperatures, respectively. In the case of Hot Mix Asphalt (HMA), the dominant failure modes include rutting, fatigue cracking and thermal cracking (Pavement Interactive 2008; and Bahia, Jenkins & van de Ven 2011).

2.3.2. The climate of South Africa

The hottest region in the country is Letaba (Limpopo province) with a mean annual temperature of 23.3°C and an average maximum temperature of 35°C (South African Weather Service 2011). The lowest temperature ever recorded in South Africa was $^{-}$18.6°C in Buffelsfontein, near Molteno, Eastern Cape on 28/06/1996 (South African Weather Service 2011). The coldest place in South Africa is Molteno, with a mean annual temperature of 11.3°C and an average annual minimum temperature of 2.8°C (South African Weather Service 2011).

Due to heat absorption, the pavement temperature rises above the air temperature. A temperature gradient is created for thick wearing courses as the interior of this layer accumulates heat. For HMA pavements, the maximum pavement temperature is taken at 20mm below the surface and is taken to be approximately 18°C higher than the air temperature (Bahia 2011). The minimum pavement temperature is taken at the pavement surface and is taken to be approximately 8°C higher than the air temperature (Bahia 2011).

For surfacing seals (thin wearing courses), the minimum and maximum temperatures are taken at the pavement surface. Figure 2.14 on the next page shows pavement surface temperatures for various regions in the country. Though these temperatures are provided, sealing works are usually carried during favourable seasons so that run-off of the emulsion is minimised.

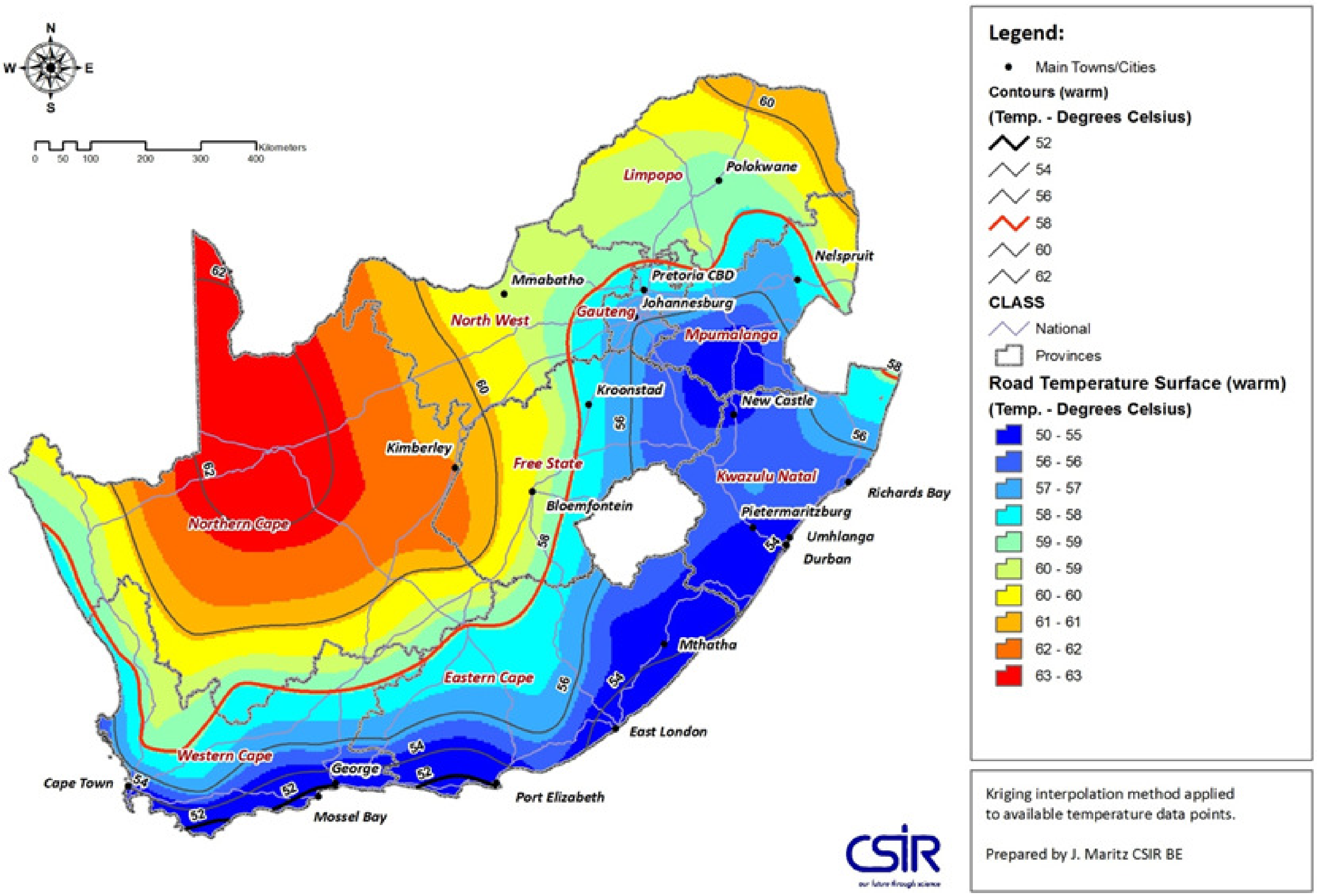


Figure 2.14 a): Maximum pavement surface temperatures for binder selection, South Africa (Jenkins 2012)

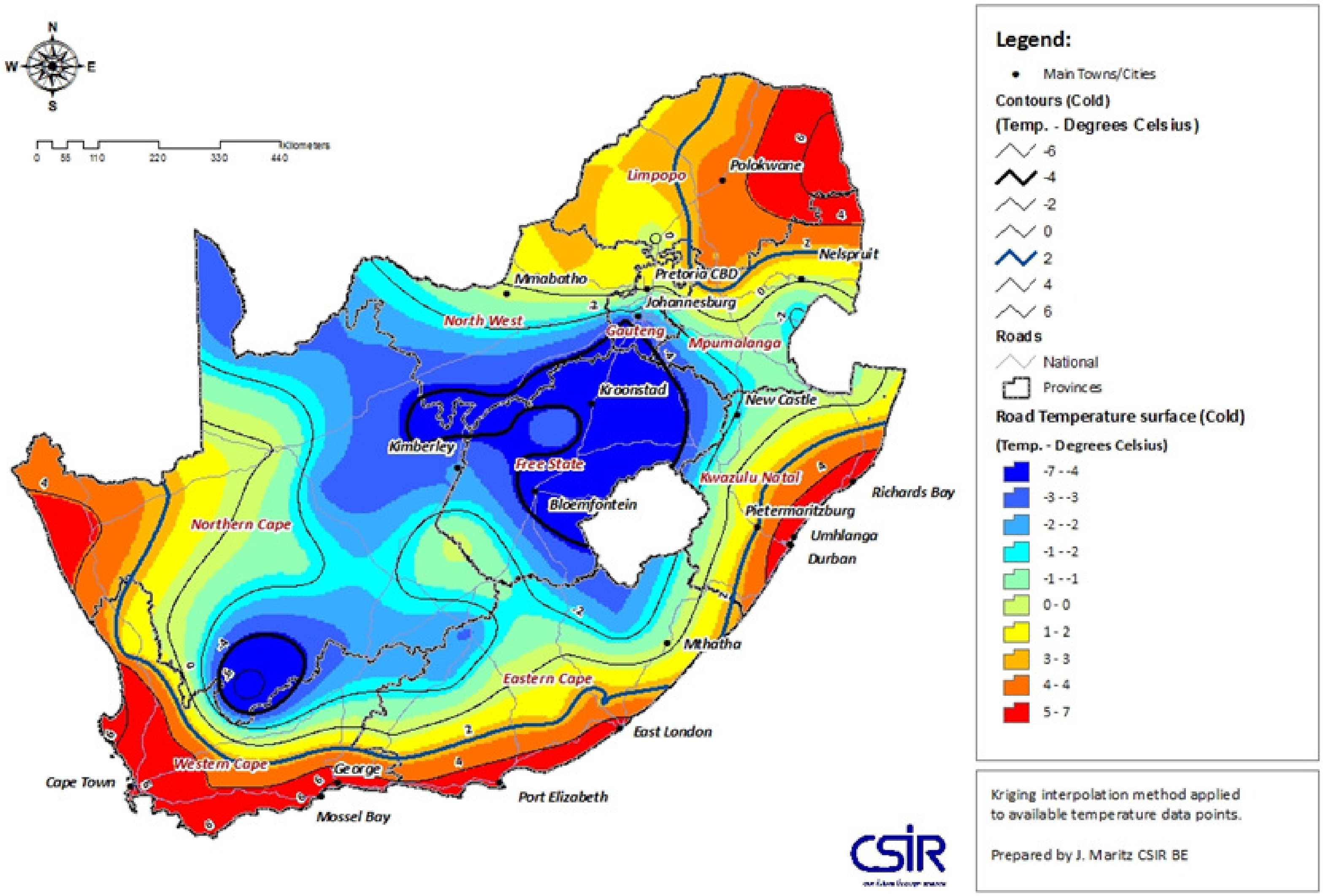


Figure 2.14 b): Minimum pavement surface temperatures for binder selection, South Africa (Jenkins 2012)

2.4. Emulsion viscosity

Viscosity is defined as the resistance to flow of a fluid. It is the measure of the internal friction of a fluid (Brookfield Engineering Labs., Inc. n.d.). If two layers of a fluid are made to move relative each other, for example in instances of pouring, spreading, spraying or mixing, a fluid with high internal friction will require more force to move these layers past each other (shear) (Brookfield Engineering Labs., Inc. n.d.). Consider the model below (Figure 2.16).

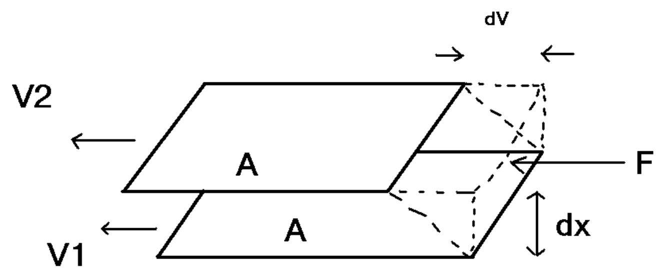


Figure 2.15: Idealisation of relative linear motion in a fluid (Brookfield Engineering Labs., Inc. n.d.; and Saint Joseph's University n.d.).

Two parallel planes of fluid of equal area *A* are separated by a distance *dx* and are moving in the same direction at different velocities, v_1 and v_2. The force required to maintain this difference in velocities is proportional to the difference in speed through the liquid, or the velocity gradient. This is expressed as $\frac{F}{A} = \eta \frac{dv}{dx}$ (Isaac Newton cited in Brookfield Engineering Labs., Inc. n.d.); where η is a constant for a given material and is called its viscosity.

'The velocity gradient, *dv/dx*, is a measure of the change in speed at which the intermediate layers move with respect to each other. It describes the shearing the liquid experiences and is therefore called **shear rate**. Its unit of measure is called the reciprocal second (sec^{-1})' (Brookfield Engineering Labs., Inc. n.d.; and Saint Joseph's University n.d.).

In the formula, $\frac{F}{A}$ is the force per unit area required to produce the shearing action. It is referred to as the shear stress. Viscosity is therefore defined mathematically by the formula $\eta = \frac{\tau}{\dot{\gamma}} = \frac{shear\ stress}{shear\ rate}$ (Brookfield Engineering Labs., Inc. n.d.; and Saint Joseph's University n.d.).

Bitumen emulsions have considerably lower viscosities compared to plain bitumen. At 60°C, the viscosity of the emulsion is in the range of 0.5-10 Poise, whereas that of bitumen is in the range of 100-4,000 Poise (James n.d.b). This low viscosity allows bitumen emulsions to be used at lower temperatures. For comparative purposes, the viscosity of water at room temperature is 1 centipoise (Barnes 2000). As a result of shearing, the binder spray viscosity is much lower than the values presented.

2.4.1. Newtonian and non-Newtonian fluids

A Newtonian fluid is one that forms a linear plot of stress against shear rate (strain rate), passing through the origin. The slope of this line is constant and gives the viscosity of the fluid. Brookfield Engineering Labs., Inc. (n.d.) states that this viscosity remains constant irrespective of the viscometer model, spindle speed or spindle size used for measurement. Viscosity is, however, specific to a given temperature. Examples of Newtonian fluids include water and thin motor oils (Brookfield Engineering Labs., Inc. n.d.).

A non-Newtonian fluid is defined as one for which the shear stress does not vary proportionally with shear rate and this fluid therefore has no constant viscosity. The viscosity of non-Newtonian fluids is dependent on the viscometer model, spindle speed and spindle size used (Brookfield Engineering Labs., Inc. n.d.). It is therefore important to indicate these parameters and the test method used when presenting viscosity results (Tia n.d.).

The most common types of non-Newtonian fluids include the following:

i. **Pseudo-plastic**: A pseudo-plastic fluid is one whose viscosity decreases as the shear rate increases (see Figure 2.17 on the next page). The most common pseudo-plastics include: paints, emulsions, and dispersions of many types. This type of flow behaviour is termed *shear-thinning* (Brookfield Engineering Labs., Inc. n.d.);
ii. **Dilatant:** A dilatant fluid is one whose viscosity increases as the shear rate increases. Examples include clay slurries, candy compounds, corn starch in water and sand/water mixtures. Dilatancy is also referred to as *shear-thickening* flow behaviour (Brookfield Engineering Labs., Inc. n.d.); and
iii. **Plastic:** A plastic fluid is one that behaves as a solid when the shear stress is below its yield strength and as a fluid when the shear stress is above the yield point (Tia n.d.). Examples are tomato ketchup and toothpaste. These items can only flow if their containers are squeezed or shaken past their yield value. Once the yield value is exceeded, the flow behaviour exhibited by these plastic fluids may be Newtonian, pseudo-plastic, or dilatant (Brookfield Engineering Labs., Inc. n.d.).

The above three types of fluids are shown in Figure 2.17 on the next page.

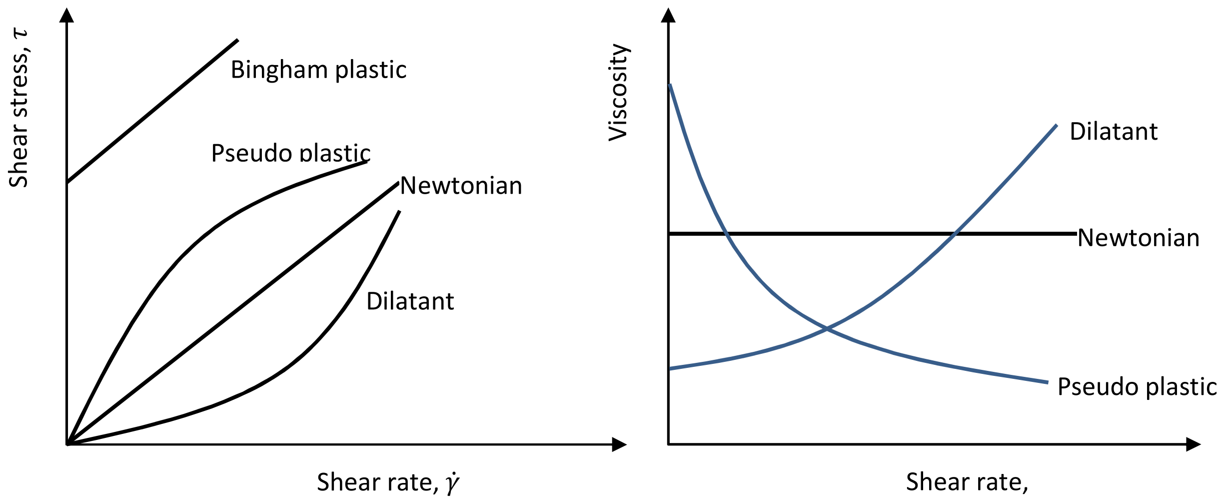


Figure 2.16: Types of viscous fluids (Brookfield Engineering Labs., Inc. n.d.; and Saint Joseph's University n.d.)

Bitumen emulsions with a bitumen content greater than 50% are non-Newtonian and show shear thinning behaviour (Rivas et al 1998). Bitumens in general, especially at low temperatures, tend to behave as slightly non-Newtonian fluids (Tia n.d., and SJ Soft Technologies 2010). They tend to be pseudo-plastic.

2.4.2. Viscosity for sprayability

Bitumen emulsion (65% binder content) is usually sprayed at a viscosity of 51-200 SFS (TRH3 2007.). This is the same as the SANS 548:2003 viscosity specification for cationic spray grade emulsions (65%) at 50^{o}C. 51 SFS corresponds to 0.10 Pa.s and 200 SFS corresponds to 0.42 Pa.s (for a conversion from centistokes to centipoise using ASTM D2161-93 and a density of bitumen emulsion of 0.9988g/cm^3 at 50^{o}C, as described by Louw 2012). The Western Cape Provincial Administration (2008) refers to the viscosity requirement given by SANS 548 but suggests a minimum of 80 SFS at 50^{o}C. Distin (2008a) recommends a viscosity range of 0.04-0.1 Pa.s for unmodified binders and 0.12-0.2 Pa.s for modified binders at the spray temperatures. Epps, Glover, and Barcena (2001), meanwhile, suggest that spray viscosities for asphalt cement and bitumen emulsions should range from 0.05-0.2 Pa.s. The viscosity values provided by Distin (2008a) and Epps, Glover, and Barcena (2001) are half those provided by SANS 548:2003. The values provided by SANS could be safe-guarding against run-off of the binder.

It is important to know the viscosity of bitumen so as to determine whether the emulsion is sprayable, that is, can form an even fan, of desired overlap (a function of pump speed) as it is sprayed from the nozzles of the bitumen distributor. This, in turn, determines the uniformity (thickness) of the applied binder on the pavement surface. The desired uniformity may not be acquired if the binder is too fluid, as it will tend to run off the camber of the pavement or down steep slopes.

2.4.3. Factors influencing the viscosity of an emulsion

As mentioned in Section 2.3.1(i)(b), the viscosity of the emulsion is influenced by the bitumen content, particle size distribution, salt content of the bitumen, temperature of the emulsion, viscosity of the bitumen, and type and dosage of emulsifier, type and dosage of emulsifier stabiliser (ScanRoad n.d.). These factors are discussed in detail below.

i. Particle size distribution

The distribution of particle sizes in an emulsion is influenced by the emulsion recipe, the design of the mill head, mill rotor speed, the gap between rotor and stator, the dwell time in the mill and the emulsification temperature (James n.d.b; and Akzo Nobel n.d.b). Smaller particle size distributions increase viscosity and improve storage stability. ‘Smaller droplets are favoured by a high energy input, a low bitumen viscosity at the emulsification temperature, by the choice of emulsifier, and by a higher concentration of emulsifier (which reduces interfacial tension)’ (James n.d.b, p.5 & 6). Figure 2.18 shows a typical particle size distribution of bitumen emulsions with different bitumen contents.

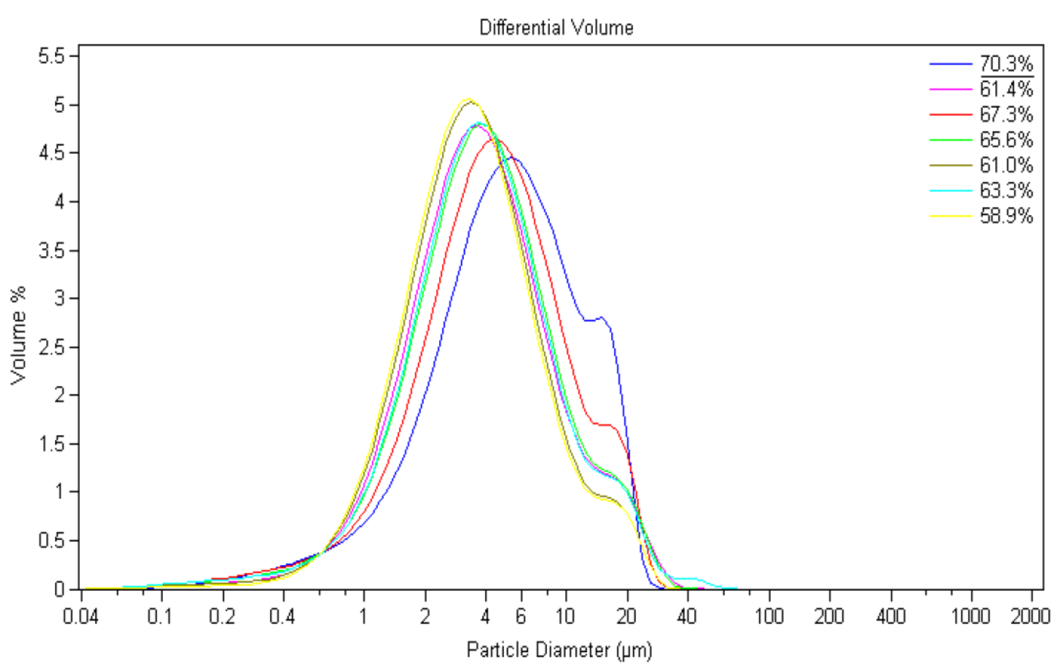


Figure 2.17: Typical particle size distribution of bitumen emulsions with different bitumen contents (James n.d.b, p.3)

Particle size distribution can be determined using the Sieve Test (ASTM D6933 - 08 Standard Test Method for Oversized Particles in Emulsified Asphalts (bitumens)) or the laser particle size analyser. No British standard exists.The South African standard used is SANS 548/SANS 309 (residue on sieving).

ii. Salt content

Akzo Nobel (n.d.) states that bitumen may contain salt left over from inadequate desalting of the crude oil. This salt can lead to osmotic swelling of the droplets in an emulsion as water is drawn into the droplet. 'This results in an increase in emulsion viscosity often followed by a decrease as the salt slowly escapes from the bitumen' (Akzo Nobel n.d.b, p.9). Calcium chloride is therefore added to cationic emulsions and sodium chloride added to anionic emulsions in order to reduce the osmosis of water into the bitumen and minimise the changes in viscosity (Akzo Nobel n.d.b; and James n.d.b). Usually 0.1-0.2% of calcium chloride or sodium chloride is added (James n.d.b).

iii. Temperature of the emulsion

The viscosity of an emulsion can be reduced by heating. As the viscosity of the bitumen droplets decreases, that of the entire emulsion decreases. Typical spray temperatures on the road range from 50-85^{o}C as provided in Tables 2.5 and 2.6 on Page 23.

iv. Viscosity of the bitumen

As in (iv) above, the viscosity of the bitumen droplets and the emulsion as a whole can be reduced by heating or using a solvent.

v. Type and dosage of emulsifier

The ability of some types of emulsifiers to produce an inverted emulsion influences the amount of water in the bitumen droplets (CME 2006). Also, formation of a multiple phase emulsion reduces the amount of free water in the emulsion, producing a coarser (more viscous) emulsion. CME (2006) notes that emulsions manufactured with naphthenic bitumen and imidazoline emulsifier have a higher bound water content. Emulsifier dosage for various grades of emulsions is provided in Table 2.8 on the next page.

Table 2. 8: Typical emulsifier use levels (adapted from Akzo Nobel n.d.b)

Emulsion type	Emulsifier level (%)	Emulsion pH	Typical emulsifier
Cationic rapid setting	0.15-0.25	2-3	Tallow diamine
Cationic medium setting	0.3-0.6	2-3	Tallow diamine
Cationic slow setting	0.8-2.0	2-5	Quaternary amine
Anionic rapid setting	0.2-0.4	10.5-12	Tall acid
Anionic medium setting	0.4-0.8	10.5-12	Tall acid
Anionic slow setting	1.2-2.5	7.5-12	Non-ionic plus lignosulphonate

vi. Type and dosage of stabiliser

The type and dosage of the chlorides used (see (iii) above) affects the osmotic uptake of water into the bitumen (Suleiman 2006). Suleiman (2006) proposes that trisodium polyphosphate be used as an alternative to sodium chloride.

2.4.4. Viscosity measurement

The viscosity of bitumen emulsions can be determined using various types of viscometers, such as the Brookfield Rotational Viscometer (RV), the Saybolt Furol (SF) viscometer, the Redwood viscometer, the Engler viscometer and the Standard Tar Viscometer (STV). Except for the RV, 'viscosity is measured as the time taken for a specific amount of emulsion to flow through the calibrated orifice' (ScanRoad n.d., p.11). This viscosity measurement is usually carried out at 25 or 50°C (ScanRoad n.d.).

For the PG grading of chip seals, three tools are proposed for measuring the critical chip seal properties. These are: (i) the Rotational Viscometer (RV), (ii) the Bitumen Bond Strength (BBS) equipment and (iii) the Dynamic Shear Rheometer (DSR) (Bahia et al 2011). These tools are shown in Figure 2.15 below (in that order from right to left).

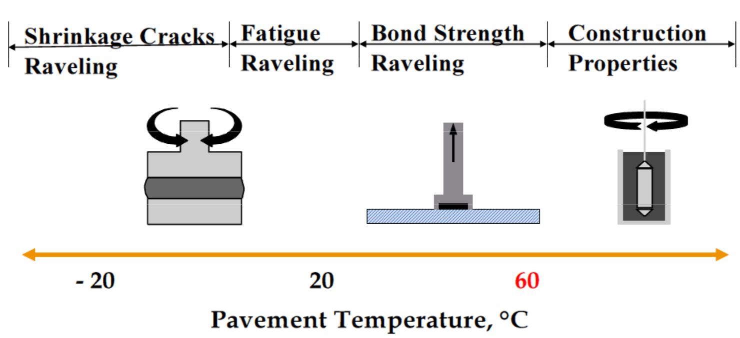


Figure 2.18: Tools for measuring the critical properties of chip seals (Bahia et al 2011, [p.13])

This figure shows that ravelling is the dominant in-service failure mode in chip seals at both high and low pavement temperatures. It also shows that viscosity for sprayability would be determined at the field application temperature (high temperature, i.e. greater than or equal to 60°C). RV testing for run-off would be carried out at the field pavement temperature. Though the critical pavement temperature can be greater than 60°C, sealing is not advisable at such high temperatures.

The RV is used in SUPERPAVE PG grading of neat bitumen because it has a better repeatability (lower than 9.6% specified for the Saybolt Furol, the next commonly used viscometer), a shorter analysis time and reduced clean-up time (Clyne, Marasteanu and Basu 2003). It is also important to note that the viscosity of bitumen can also be measured using the DSR.

2.4.3.1. Choice of suitable viscometer for emulsions

Salomon et al (n.d.) performed a study on three instruments used to measure the rotational viscosity of bitumen emulsions. These were the Brookfield RV, the Cannon Marine Fuel Viscometer and the Bohlin CVO Rheometer (CVO). It should be noted that in the Cannon Marine Fuel Viscometer test, a paddle spindle was used, and that the Bohlin instrument was a DSR. Results showed that the viscosity obtained from the Cannon Marine Fuel Viscometer had the highest correlation ($R^2 > 0.9$) with the viscosity measured from the SF viscometer. The RV and DSR had an R^2 of 0.8. From this, MARC recommended the Rotational Paddle viscometer as a more suitable piece of equipment to measure the viscosity of bitumen emulsions, and an ASTM standard was produced (Johannes 2012).

Although good correlation between the RV and SF, and the paddle and SF, was reported, a literature review conducted by MARC revealed that there is no fundamental relationship between the RV and SF or the paddle and SF (Johannes 2012). It furthermore revealed that the flow of a fluid within the SF viscometer is complex because the shear rate continuously changes with time during the test. Flow in the viscometer is driven by the hydraulic head of the fluid, which changes with time as the viscometer empties. Based on this, MARC concluded that the SF is not a good instrument for time-dependent liquids such as most bitumen emulsions (Johannes 2012).

The claim that no relationship exists between the RV and SF was verified by one of the emulsion producers in the United States. Johannes (2012) reports that this producer made measurements on the same emulsions with both the RV and the SF. A linear regression model relating the two equipment was obtained. This model had a very high R-square of approximately 0.85. The emulsions were then tested in the RV, and the developed model used to predict what the viscosity was going to be in the SF. The results were scattered with no clear relationship between the two instruments (Johannes 2012). The reason for the scatter is that the RV and SF subject the emulsion to different test conditions, i.e. different shear stresses and shear rates (Johannes 2012).

2.4.3.2. The Brookfield rotational viscometer

i. Description

An example of the Brookfield RV is provided in Figure 2.19 below. The components and functioning of the viscometer is subsequently explained.

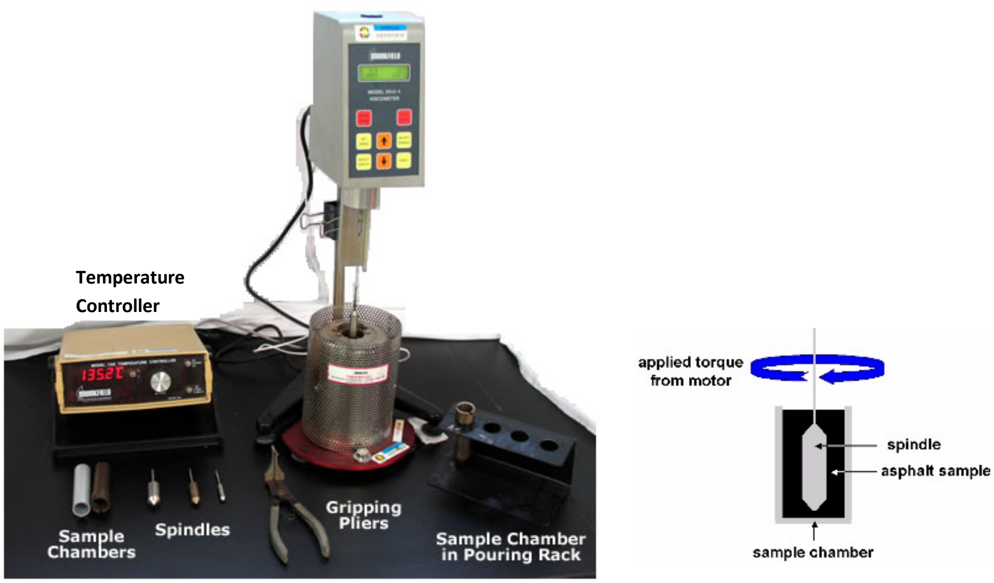


Figure 2.19: Brookfield Rotational Viscometer and thermosel system (Pavement Interactive 2011)

The Brookfield viscometer consists of a thermosel, spindle, motor, control keys and digital readout. The motor is used to power the spindle through the torsional spring of the viscometer. As the spindle rotates, the torsional spring winds. This coiling is detected by a rotary transducer and a reading is displayed on the screen of the digital read out (McGennis, Shuler and Bahia 1994).

‘The thermosel system consists of the sample chamber, thermo-container and temperature controller. The sample chamber is a stainless steel cup in the shape of a test tube. An extracting tool is used to handle the sample chamber when hot. The thermo-container holds the sample chamber and consists of electric heating elements that maintain or change test temperature’ (McGennis, Shuler and Bahia 1994, p.49).

ii. Test procedure for viscosity determination

The procedure followed is described below, in brief.

a. A sample of bitumen is poured into the sample chamber and this is placed in the thermo-container.
b. The temperature of the sample is monitored on the temperature controller and left to equalise before the sample can be tested (McGennis, Shuler and Bahia 1994, p.49).
c. The spindle is lowered into the bitumen and rotated at a constant speed.
d. The torque required to maintain this speed is measured and converted into the viscosity of the binder. A viscosity reading in Pas is displayed automatically by the RV (Pavement Interactive 2011).
e. The digital display can be set to show viscosity, spindle speed, spindle number and the test temperature (McGennis, Shuler and Bahia 1994). These are required for the test report.

The SUPERPAVE PG bitumen binder tests for HMA are conducted at 135^{o}C and a speed of 20 RPM (McGennis, Shuler and Bahia 1994; and Pavement Interactive 2011). The 135^{o}C corresponds to the temperature at which bitumen is heated during manufacture and construction. The 20 RPM corresponds to the rotational speed during pumping, mixing and compaction. Bitumen emulsions use different test conditions.

The standards used for determining bitumen viscosity using an RV are AASHTO T 316 and ASTM D 4402: Viscosity Determination of Asphalt (bitumen) Binder Using Rotational Viscometer. ASTM D 7226-06 is the Standard Test Method for Determining the Viscosity of Emulsified Asphalts (bitumens) using a Rotational Paddle Viscometer.

iii. Factors that may influence viscosity readings with the RV

As mentioned in Section 2.4.1, bitumen emulsions are non-Newtonian fluids. The viscosity of these emulsions is dependent on shear rate. This, in turn, is dependent on the rotational speed of the spindle, the size and shape of the spindle, the size and shape of the container used and hence the distance between the container wall and the spindle surface (Brookfield Engineering Laboratories, Inc. n.d.a). These factors are discussed below.

a. Spindle/speed selection

The spindle size and speed to be used for an unknown fluid is normally obtained by trial and error (Brookfield Engineering Laboratories, Inc. n.d.b; and Brookfield Engineering Laboratories, Inc. n.d.a). Brookfield Engineering Laboratories, Inc. (n.d.a) states that an appropriate selection will result in measurements made between 10-100% torque. It gives the following rules as a guide:

> *i. Viscosity range is inversely proportional to the size of the spindle*
> *ii. Viscosity range is inversely proportional to the rotational speed*
> *In other words, to measure high viscosity, choose a small spindle and/or a slow speed. If the chosen spindle/speed results in a reading above 100%, reduce the speed or choose a smaller spindle. Experimentation may reveal that several spindle/speed combinations will produce satisfactory results between 10-100%. In such a circumstance, any of the spindles may be selected* (Brookfield Engineering Laboratories, Inc. n.d.a, p.25).

It is recommended that, if a sample has historically been tested using a particular methodology (i.e. instrument, speed, spindle, container, temperature and test time), the user should maintain that same methodology (Brookfield Engineering Laboratories, Inc. n.d.a). This sets common ground for the comparison of viscosities.

McGennis, Shuler and Bahia (1994) state that the viscosity of the binder being tested determines the choice of spindle. These authors add that many binders can be tested using spindle No. 21 and 27; of these, spindle No. 27 is the most frequently used. However, Bahia et al (2010) recommend the use of spindle No. 21 in testing emulsions. This is because a bitumen emulsion is much less viscous than plain bitumen.

b. Geometry dependency

Salomon et al (n.d.) state that the final emulsion equilibrium microstructure varies under different geometries of the sample container. This results in different equilibrium viscosity values (Salomon et al n.d.). There are three basic categories of measuring geometries, namely: (i) cone and plate; (ii) parallel plates; and (iii) cup and bob (Bohlin Instruments Ltd 1994). These measuring geometries are shown in Figure 2.20 on the next page.

c. Calibration and standardisation

Calibration of the RV is necessary in order to obtain accuracy in the measured output. The following components are considered:

i. The rotary transducer: The accuracy of this is checked using a reference fluid of known viscosity (McGennis, Shuler and Bahia 1994); and

ii. The temperature detector: The accuracy of the temperature detector is validated by placing a bitumen sample in the testing chamber and equilibrating it to a given temperature. The displayed temperature is then verified using a calibrated thermometer (McGennis, Shuler and Bahia 1994).

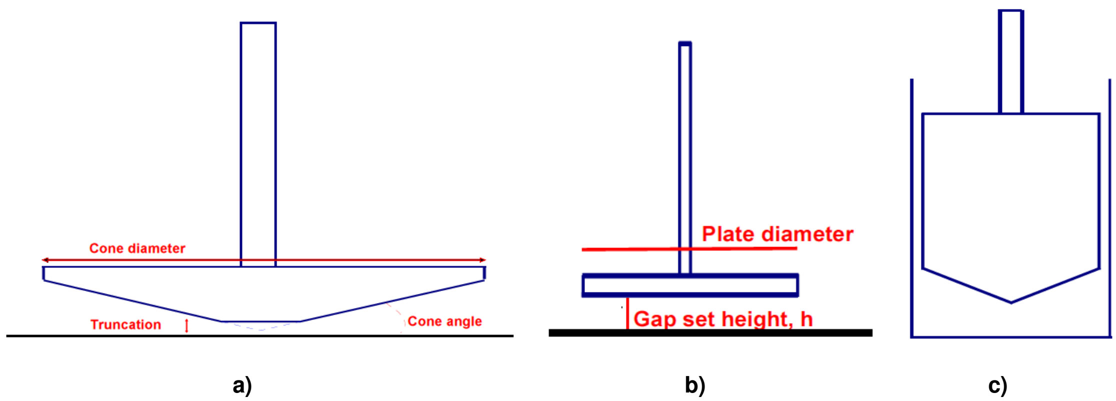


Figure 2.20: Measuring geometries used to determine rheological properties of binders: a) Cone and plate, b) Parallel plate and c) Cup and bob (Bohlin Instruments Ltd 1994)

2.4.3.3. Shear rates

The shear rates chosen for use in the RV test are meant to simulate field application of the binder. Since the binder undergoes different shear rates at circulation (within the bitumen tank, to the spray bar and back), spraying through the nozzles and at the spray surface as it runs off, it is important to capture all these scenarios for performance testing purposes.

Barnes (2000) and Brookfield Engineering Laboratories, Inc (n.d.b) give the following range of shear rates for various physical applications in daily life (see Tables 2.9 and 2.10 on the next pages). Bohlin Instruments Ltd (1994) also provides a range of shear rates (see Table 2.11 on page 53).

The shear rate for spraying (atomisation/air spraying) is approximately 10^5- 10^6 s^{-1} (Barnes 2000), 10^4- 10^5 s^{-1} (Bohlin Instruments Ltd 1994) and 10^3-10^5 s^{-1} (Brookfield Engineering Labs., Inc. n.d.b). The shear rate for bitumen spraying would be lower than that for air spraying because the bitumen does not atomise, as it is desired that it remains a liquid. Johannes (2012) states that the shear rate for spraying bitumen may be in the range of 1000-3000 s^{-1}. She notes, however, that at 183 RPM, the viscosity of some emulsions drops to below 0.1 Pa.s. This would imply that at very high shear rates, such as 1000 s^{-1}, one would obtain zero readings. Johannes (2012) concludes that it would not be necessary to use high shear rates when studying sprayability in the RV. Another reason for this is that the Brookfield viscometer has a rotational speed limit of 200 RPM.

The SHRP researchers that developed the RV test for hot binders quoted a value of 3000 s^{-1} based on industry input (Johannes 2012). Though such a high value was quoted, the standard RV test is conducted at 20 RPM because a previous study found that the viscosity of hot binders does not change much beyond 20 RPM (Johannes 2012). For comparative purposes, 4.65 s^{-1} = 5 RPM, 46.5 s^{-1} = 50 RPM, 173 s^{-1} = 183 RPM (Bahia et al 2011; and Johannes et al n.d.).

Table 2.9: Typical shear rate ranges for various physical applications (Barnes 2000)

Situation	Shear Rate Range / s^{-1}	Examples
Sedimentation of fine powders in liquids	10^{-6} - 10^{-3}	Medicines, paints, salad dressing
Levelling due to surface tension	10^{-2} - 10^{-1}	Paints, printing inks
Draining off surfaces under gravity	10^{-1} - 10^{1}	Toilet bleaches, paints, coatings
Extruders	10^{0} - 10^{2}	Polymers, foods soft solids
Chewing and swallowing	10^{1} - 10^{2}	Foods
Dip coating	10^{1} - 10^{2}	Paints, confectionery
Mixing and stirring	10^{1} - 10^{3}	Liquids manufacturing
Pipe flow	10^{0} - 10^{3}	Pumping liquids, blood flow
Brushing	10^{3} - 10^{4}	Painting
Rubbing	10^{4} - 10^{5}	Skin creams, lotions
High-speed coating	10^{4} - 10^{6}	Paper manufacture
Spraying	10^{5} - 10^{6}	Atomisation, spray drying
Lubrication	10^{3} - 10^{7}	Bearings, engines

Table 2.10: Typical examples of shear rates (Brookfield Engineering Laboratories, Inc. n.d.b)

Situation	Typical range of shear rates (s^{-1})	Application
Sedimentation of fine powders in a suspending liquid	10^{-6} - 10^{-4}	Medicines, Paints
Levelling due to surface tension	10^{-2} - 10^{-1}	Paints, printing inks
Draining under gravity	10^{-1} - 10^{1}	Painting and coating, toilet bleaches
Extruders	10^{0} - 10^{2}	Polymers
Chewing and swallowing	10^{1} - 10^{2}	Foods
Dip coating	10^{1} - 10^{2}	Paints, confectionery
Mixing and stirring	10^{1} - 10^{3}	Manufacturing liquids
Pipe flow	10^{0} - 10^{3}	Pumping, blood flow
Rubbing	10^{2} - 10^{4}	Application of creams and lotions to the skin
Spraying and brushing	10^{3} - 10^{5}	Spray-drying, painting, fuel atomization
Milling pigments in fluid bases	10^{3} - 10^{5}	Paints, printing inks
High speed coating	10^{5} - 10^{6}	Paper
Lubrication	10^{3} - 10^{7}	Gasoline engines

Table 2.11: Typical shear rates for some standard processes (Bohlin Instruments Ltd 1994)

TYPICAL SHEAR RATE'S FOR SOME STANDARD PROCESSES

Process	Typical range (S^{-1})
Spraying	10^{4} - 10^{5}
Rubbing	10^{4} - 10^{5}
Curtain coating	10^{2} - 10^{3}
Mixing	10^{1} - 10^{3}
Stirring	10^{1} - 10^{3}
Brushing	10^{1} - 10^{2}
Chewing	10^{1} - 10^{2}
Pumping	10^{0} - 10^{3}
Extruding	10^{0} - 10^{2}
Levelling	10^{-1} - 10^{-2}
Sagging	10^{-1} - 10^{-2}
Sedimentation	10^{-1} - 10^{-3}

Brookfield Engineering Labs., Inc. (n.d.b) states the following:

> *It is frequently impossible to approximate projected shear rate values during measurement because these values fall outside the shear rate range of the Viscometer. In this case, it is necessary to make measurements at several shear rates and extrapolate the data to the projected values. This is not the most accurate method for acquiring this information, but it is often the only alternative available, especially when the projected shear rates are very high. In fact, it is always advisable to make viscosity measurements at several shear rates to detect rheological behaviour that may have an effect on processing or use* (Brookfield Engineering Labs., Inc. n.d.b, p.19).

From the Tables 2.9 and 2.10 on the previous pages, the drain off shear rate is 10^{-1}-10^{1} (Barnes 2000 & Brookfield Engineering Labs., Inc. n.d.b). This is most likely applicable to surfaces close to vertical.

2.4.5. Sprayability and drain-down

2.4.4.1. Background to test methods

Salomon and Palasch (n.d.) discuss a study that determined the equilibrium viscosity of bitumen emulsions using an RV. This study performed tests at 50^{o}C, 50 RPM and used spindle 21 (abbreviated as method 50-50-21). It was found that the emulsions, which were thixotropic, attained an equilibrium viscosity after approximately 20 minutes.

Method 50-50-21 was proposed as a test method for emulsions including using emulsion equilibrium viscosities for road emulsion specifications (Salomon and Palasch n.d.). This method was adapted by Bahia et al (2009) when these authors investigated the relationship between Saybolt Furol and the RV. Salomon et al (n.d.) also used Method 50-50-21 to compare the RV, paddle viscometers and Bohlin DSR to the Saybolt Furol viscometer.

Salomon and Palasch (n.d.) further describe the equilibrium viscosity of bitumen emulsion. These authors state that ‘bitumen emulsions have got a microstructure of aggregate droplets (flocs) that under steady shear break into individual droplets’. As the flocs break down, the emulsion experiences a decrease in viscosity until an equilibrium viscosity is attained (Salomon and Palasch n.d, [p.2]). The rheogram of bitumen emulsions would have three regions as shown in Figure 2.21 on the next page.

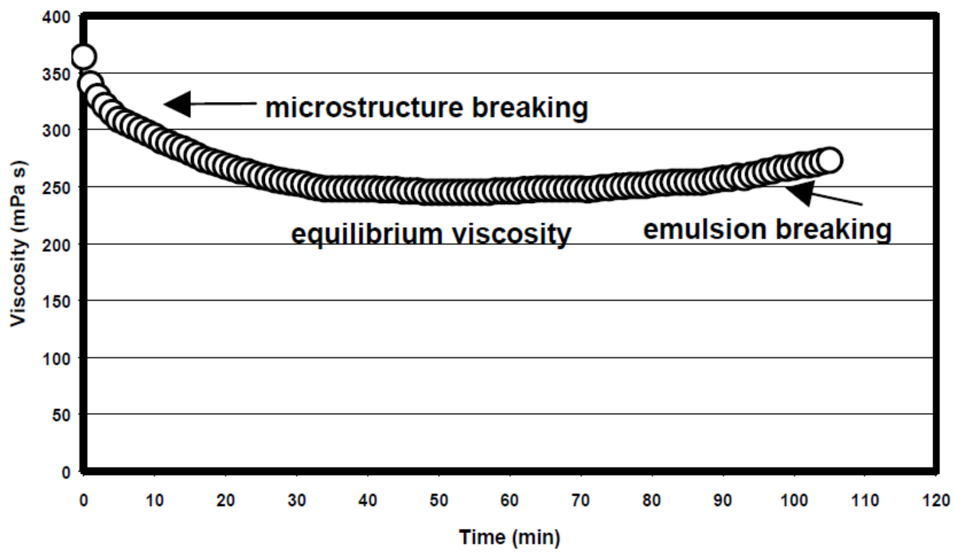


Figure 2.21: CRS-2P time dependent viscosity at 50°C and 50 RPM showing the three viscosity regions (Salomon and Palasch n.d.)

2.4.4.2. The 3 step test

Zhai, Salomon & Milliron (n.d.) developed the three-step (low shear rate – high shear rate – low shear rate) test to simulate the spraying and setting characteristics of different types of emulsions. This test was adapted from the paint industry, where it is used to study the spraying and sagging behaviour of emulsion paints (Johannes, Hanz & Bahia n.d.). Eight types of emulsions were studied by Zhai, Salomon & Milliron (n.d.) using a controlled stress Bohlin CVO Dynamic Shear Rheometer (DSR). The test protocol used is shown in Table 2.12 on the next page.

Johannes, Hanz & Bahia (n.d.) also evaluated three types of emulsions, namely CRS-2P, CQS-1H and CQS-1HL. These authors used the 3-step test and an RV. The test protocol that was followed is also provided in Table 2.12.

In the 3-step test, the sample is subjected to a shear rate in step 1; the shear rate is suddenly increased to that shown in step 2 and then suddenly decreased to that used in step 3, as illustrated in Table 2.12. A viscosity *versus* time plot is generated to monitor the change in rheological properties (Zhai, Salomon & Milliron n.d.). Zhai, Salomon & Milliron (n.d.) state that the 3-step test can be used to evaluate the run-off potential of bitumen emulsions.

Zhai, Salomon & Milliron (n.d.) found that the samples considered (CRS -2P, CMS-2 and CRS-2) behaved differently with regard to the rate and extent to which viscosity was lost at a high shear rate and subsequently regained at a low shear rate. Typical results

Table 2.12: Comparison of test protocols for the 3-step test

Parameter	Test procedure		Significance/Representation	
	Zhai, Salomon & Milliron (n.d.)	Johannes, Hanz & Bahia (n.d.)	Zhai, Salomon & Milliron (n.d.)	Johannes, Hanz & Bahia (n.d.)
Name of test	3-step test (Time Sweep Test)	3-Step Shear Test	Test developed to evaluate viscosity of bitumen emulsions during spraying and during run-off after it has reached the pavement surface	Test developed to evaluate sprayability and drain-out of bitumen emulsions (as in the previous column)
Material	Emulsion residue	Emulsion		
Equipment	DSR	RV		
Test temperature	30℃	40℃ for drain-out, 60℃ for sprayability (sprayability ending at step 2)		
Shear rate – Step 1	0.1 s^{-1} for 180 seconds	4.65 s^{-1} or 5 RPM for 15 minutes	Simulates storage of bitumen emulsions in the tank (low shear)	Simulates the low shear rate conditions that bitumen emulsions are subjected to during storage in the storage tank or in the distribution truck.
– Step 2	100 s^{-1} for 180 seconds	173 s^{-1} or 183 RPM for 5 minutes	Simulates spraying and/or pumping of the bitumen emulsions	Simulates higher shear rate applications such as spraying or pumping of bitumen emulsions
– Step 3	0.1 s^{-1}	4.65 s^{-1}	Simulates the emulsion's viscosity recovery after spraying on the pavement surface	Simulates the low shear rate conditions after the emulsion has been applied. It allows for the evaluation of the binder's ability to recover its viscosity after subjection to a high shear

presented by Zhai, Salomon & Milliron (n.d.) and Johannes, Hanz & Bahia (n.d.) are shown in Figures 2.22-2.24.

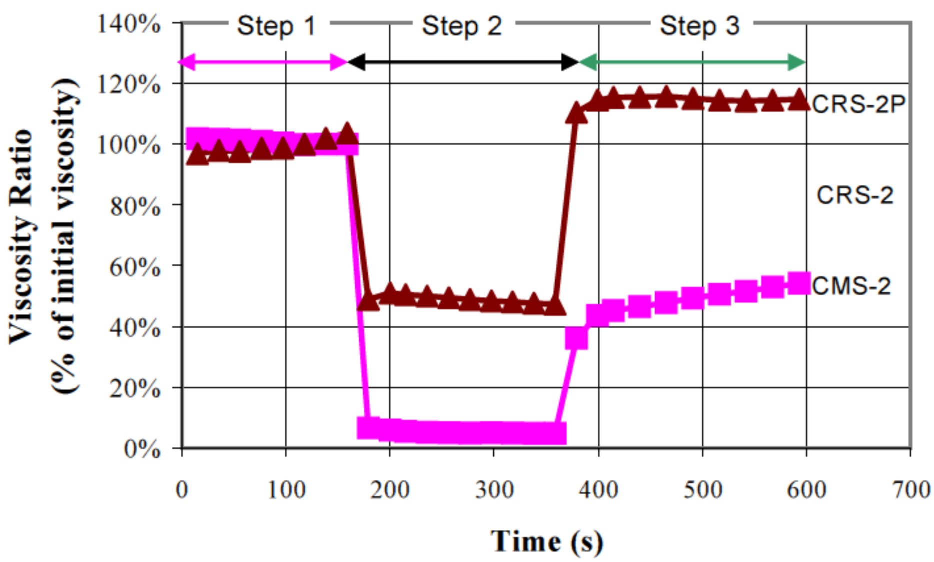


Figure 2.22: 3-Step test results using a DSR at 30°C (Zhai, Salomon & Milliron n.d.)

The viscosity ratio was defined as the ratio between viscosity values at different times and viscosity values at the end of step 1 (Zhai, Salomon & Milliron n.d.).

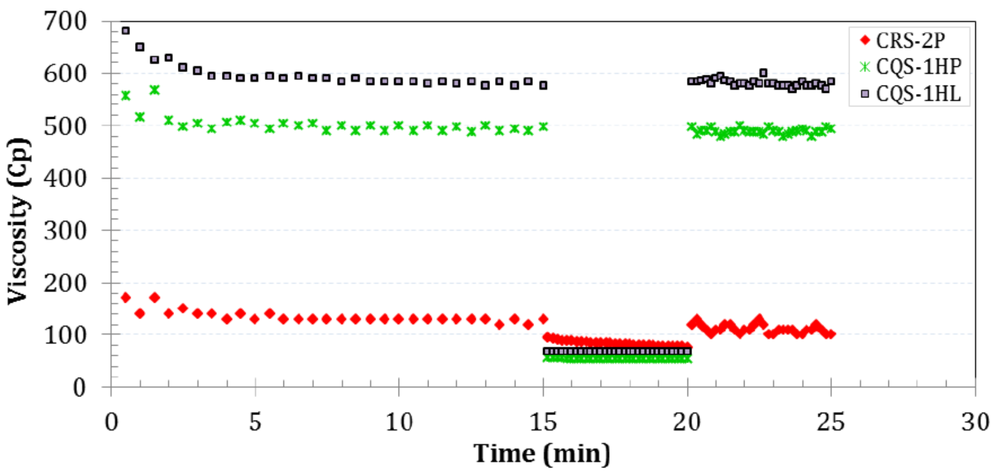


Figure 2.23: 3-Step test results using an RV at 40°C (Johannes, Hanz & Bahia n.d.)

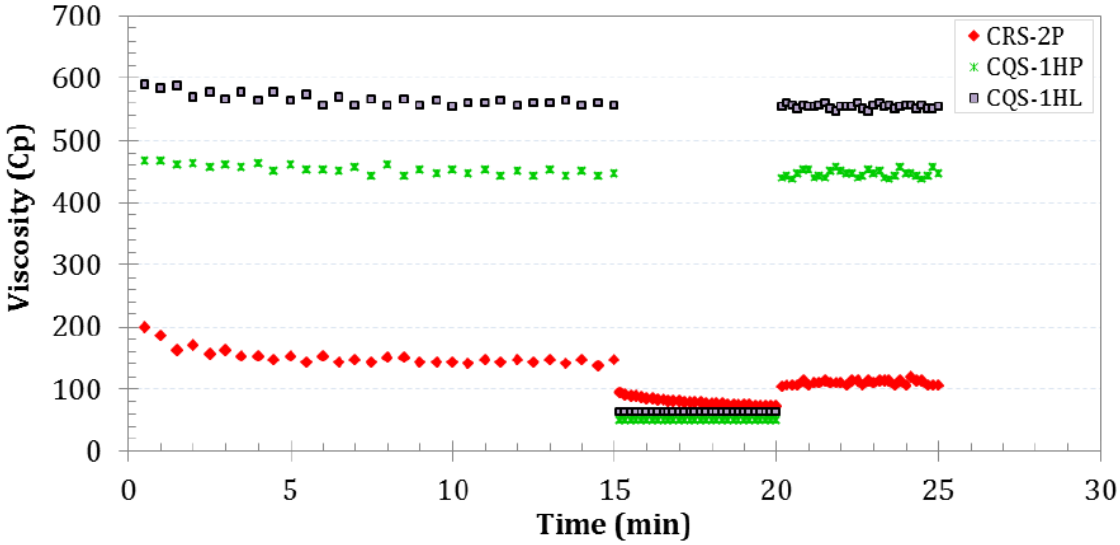


Figure 2.24: 3-Step test results using an RV at 60°C (Johannes, Hanz & Bahia n.d.)

Johannes, Hanz & Bahia (n.d.) used spindle 21, and rotational speeds of 5 RPM and 183 RPM because these were the speed limits of the Brookfield RV DVIII used in the study. Sprayability was calculated as the average of the last 5 points at a rotational speed of 183 RPM and the field spray temperature (60°C) – step 2. Run-off was calculated as the average of the last 5 points at 5 RPM and the average pavement temperature during construction (40°C) – step 3. A viscosity range of 50-75 cP was recorded for step 2 and 100-550 cP for step 3 (Johannes, Hanz & Bahia n.d.)

From the viscosity-time graphs plotted, Johannes, Hanz & Bahia (n.d.) observed that the 3-step shear test is sensitive to the properties of the base binder, the chemistry of the emulsion and the type of polymer used in modification. It was also observed that all the emulsions tested showed minimal time dependency.

Johannes, Hanz & Bahia (n.d.) note that there are no viscosity limits for sprayability and run-off to differentiate between good and poor performing binders.

2.5. Existing limits for construction performance grading of emulsions for surfacing seals

Table 2.13 below shows limits that have been compiled for the performance grading for surfacing seals. These limits are compared to those of HMA.

Table 2.13: Existing limits for the performance grading of emulsions (construction-related parameters)

		Measure	**Criteria**		
			Emulsions for seals	**Plain bitumen for Seals**	**HMA**
Construction performance properties	Stability	Cylinder storage, 24hrs	1% (ASTM D977-97)	NA	NA
	Breaking rate	Silica powder (sikasol), g	_g of silica powder (required for break)	NA	NA
	Run-off /sprayability	Viscosity, Pa.s	_	0.1-0.15 Pa.s (Epps, Glover & Barcena 2001; and Walubita, Epps-Martin & Glover 2005)	0.12-0.65 Pa.s (Van de Ven, Jenkins & Bahia 2004), 3 Pa.s (SUPERPAVE)
	Wetting of chip stones	Adhesion strength, Pa	> 850 kPa (Miller et al 2010)	_	NA

Epps, Glover & Barcena (2001) and Walubita, Epps-Martin & Glover (2005) used the RV to determine the temperature at which the binder viscosity fell within a range of 0.10-0.15 Pa.s. This viscosity range was deduced from recommended values of 0.05-0.20 Pa.s obtained from previous literature. This literature included McLeod (1963), Herrin (1968), Epps, Gallaway & Hughes (1981) and Elmore, Solaimanian, McGennis, Kennedy & Phromsorn (1995). Walubita, Epps-Martin and Glover (2005) considered seven types of modified binders, two of which were emulsions. Research presented by Walubita, Epps-Martin & Glover (2005) is a continuation of the research done by Epps, Glover & Barcena (2001) concerning Performance-Graded binder specification for surface treatments.

2.6. Conclusion

The literature explored showed that:

i. Viscosity of bitumen emulsions is not only affected by shear rate but also by the particle size distribution, emulsion formulation and temperature;
ii. The best way to measure sprayability and run-off is by using the 3-Step Shear Test;
iii. The shear rate for run-off ranges from 0.1 to 10 s^{-1}, though the gradient was not specified; and
iv. At present, there are no limits to distinguish between good and poor binders. The viscosity for sprayability and run-off is still based on experience.

In the light of this literature, the current study focuses on evaluating the drain-down performance of unmodified cationic spray grade emulsion (65%), the most commonly used unmodified binder for spray seals. This study aims at providing greater insight into the run-off behaviour of this type of emulsion in a bid to establish such limits. A detailed description of the research design and methodology used is presented in the next chapter.

Chapter 3 : Research design and methodology

'Research is to see what everybody else has seen, and to think what nobody else has thought' — Albert Szent-Gyorgyi

3.1. Introduction

In order to determine the run-off performance of emulsions for seals, laboratory scaled models of seal surfaces were constructed. The emulsion was then sprayed onto the surfaces using a spray bar mounted on a conveyor. Three variables were considered, namely: (i) gradient, (ii) spray rate and (iii) texture depth. Other variables, such as pavement temperatures, emulsion temperature and emulsion type (emulsion viscosity), were kept constant.

The following reasons were used to justify the above mentioned choices:

i. It was considered more feasible to construct seal surfaces rather than perform an *in-situ* test, because this would allow the author to vary the gradient, collect the runoff with ease and speedily change between seal types, which were within reach (i.e., in the laboratory). If the seals were on site, they would be dispersed by a certain amount of kilometres. This would require some time to move from one seal to the next;
ii. The three particular variables mentioned before were considered because these are the most essential. Pavement and emulsion temperatures are variables which would influence performance; however, they are assumed to be constant for the experiment. An emulsion temperature of 60°C was chosen because it is the recommended/specified field application temperature. Experience has shown that the binder is sometimes sprayed below 60°C, though specifications should be followed. In other words, 60°C is a critical enough temperature for viscosity reduction required for sprayability. On-site application of the emulsion at its maximum storage temperature (85°C) would not be advisable as it would run off more easily;
iii. The cationic spray grade emulsion (65%) was the binder used because there is a limited range of emulsions used to construct surfacing seals in South Africa. These include cationic spray grade (65% or 70%), SC-E1 (3% latex) and SC-E2 (5% latex) (Louw 2012). In discussion with a main local supplier, it became evident that polymer modified binders usually pass the run-off test and were therefore not considered. It should be noted that CRS-1 refers to a 60% binder content and CRS-2 to a binder content greater than or equal to 65% (Louw 2012).

For various combinations of gradient, spray rate and texture depth, the amount of runoff was recorded. Results were then analysed to determine the conditions under which the bitumen emulsion performed optimally.

3.2. Limitations

The current study design and methodology had the following limitations:

i. Spray board dimensions: The spray surfaces could only be constructed within the confinement in which the conveyor could operate. This space had to be used effectively to provide a collection area as well. The weight of the spray board and the area covered by chip stones also had to be limited so that the spray surface could be lifted onto and off the raised platform manually; and
ii. Pavement/seal surface temperature: The pavement temperature could not be raised to a critical value, say 40^{o}C, because the area covered by the available infra-red heater was small and by the time the whole pavement was heated, the starting point had cooled. The many tasks involved in the experiment also did not allow this to be practical. The pavement was therefore tested at ambient temperature (23-25^{o}C).

3.3. Variables influencing runoff

3.3.1. Vertical and horizontal gradient

Note that the term “gradient” is used to refer to the resultant or maximum gradient as a result of the vertical and horizontal alignment of the road. Under the horizontal alignment lies the cross-fall or super-elevation.

On horizontal curves, the most critical gradient is that due to super-elevation. Super-elevation and tyre friction are the most important factors in the stability of a vehicle on horizontal curves. These two factors provide the centripetal force required to keep a vehicle moving in a circular curve. High super-elevations improve driver comfort during dry conditions by requiring less frictional force but cause hydroplaning of slow-moving vehicles (slippage towards the inside of the curve) during wet conditions (Oregon State University, Portland State University & the University of Idaho 2003). There is therefore a limit to the maximum super-elevation a horizontal curve can have.

In South Africa, the maximum super-elevation permitted on freeways is 10% (CSIR 2000). Krammes & Garnham (n.d.) give the maximum super-elevations for various types of roads as 6% for urban freeways, 8% for rural freeways and 10% for rural dual carriage and single lane roads. TRH3 (2007) and Manual 10 (2012) provide similar recommendations for the maximum vertical gradient and super-elevation on which emulsions can be used (see Table 3.1 on below). The recommended application viscosity is also provided in this table.

Table 3.1: Recommended maximum gradients and application viscosities (TRH3 2007: Table 5-2)

Binder type		Application viscosity	Maximum gradient
Bitumen grade:	80/100 pen 150/200 pen	40 - 100 cSt 40 - 100 cSt	12% 10%
Cutback bitumens:	MC3000 MC 800	3000 - 6000 cSt 800 - 1600 cSt	8% 6%
Emulsions:	60% 65%	20 - 50 Saybolt Furol secs 51 - 200 Saybolt Furol secs	6% 8%

For this study, only two gradients, 4% and 6%, were considered. 2% is the normal cross-fall of the road on which the binder is less likely to run off, and 8% was considered too steep, requiring the use of highly viscous or modified binders.

3.3.2. Texture depth

Texture depths that could simulate new construction and reseal were considered. For new construction, run-off is evaluated on top of the base; if a double seal is used, run-off is also evaluated on top of the first seal layer. Table 3.2 on the next page highlights the different types of surfacings available (TRH3 2007).

The following surface textures were considered:

i. A 13.2mm seal. This was selected because it contains the maximum aggregate size most favourable for skid resistance.

   Coarse textured surfaces are preferred on rural high speed roads because these provide better skid resistance. Smooth textured surfaces, on the other hand, are preferred for city streets because these are easier to clean and generate less noise (TRH3 2007). There is a limit to the coarseness of texture used because of the nuisance of tyre noise, its effect on riding comfort and windshield damage by large loose stones. The largest size of aggregate, therefore, recommended for single seals is 13mm (19mm in exceptional cases) (TRH3 2007).

ii. A 9.5 mm seal. This was selected because it contains the maximum aggregate size recommended for low tyre noise levels in urban areas. The maximum size of aggregate used in the top layer of pavements in the urban area does not exceed 9.5mm in order to reduce high noise levels (TRH3 2007).

Table 3.2: Types of surfacings (TRH3 2007)

Abbreviation	Surfacing
S3	Sand seal
S7	Coarse slurry seal
S1	Single seal
S2(9)	Double seal with 9.5mm aggregate and sand
S2(13)	Double seal with 13.2mm aggregate and sand
S4(13)	Cape seal with 13.2mm aggregate and one layer of slurry
S2(13/6)	Double seal with 13.2mm aggregate and a layer of 6.7mm aggregate
S2(19/9)	Double seal with 19mm aggregate and a layer of 9.5mm aggregate
S2(19/6)	Double seal with 19mm aggregate and one or two layers of 6.7mm aggregate
S4(19)	Cape seal with 19.0mm aggregate and two layers of slurry
AC	Asphalt

iii. A fine slurry seal. This was selected because it would provide the least texture depth as it is composed of the smallest aggregate sizes. A slurry seal is usually used as pre-treatment for varying texture depths before a stone seal is applied. Varying textures may have resulted from aggregate stripping in patches, excessive patching of the road or fattiness only in the wheel tracks (TRH3 2007). Slurry seals also form part of the top layer of the cape seal, which may require a reseal.

Higher chip stone sizes were not considered because run-off decreases with an increase in chip size, as the texture depth tends to trap and contain the emulsion. Higher stone sizes were also not considered because they are rarely used. For a new construction, a laterite and gravel base would have been considered but this was not found to be necessary in the current study because the texture of these bases was covered within the texture range chosen (from fine slurry to 13.2 mm seal).

3.3.3. Spray rates

The three types of seals, namely a 13.2mm seal, 9.5mm seal and a fine slurry seal were each constructed on separate boards of dimensions 2.44m x 1.22m x 0.021m. In order to construct the 13.2 and 9.5 mm seals, the binder spray rate and aggregate spread rate had to be determined. The spray rates for evaluation/use during the run-off test also needed to be determined. The procedure for determining binder spray rate as explained in TRH3 (2007) was reviewed. This requires a number of input variables particular to a given road and that require testing. These variables include corrected ball penetration value, equivalent light vehicles, average least dimension of aggregates, texture depth, flakiness index (required for adjustment for aggregate spread rate), climate and gradient. The researcher was not considering any given road in particular and it was found unnecessary to perform these tests with the option that average spray rate values commonly found in practice could be used.

3.3.3.1. Recommended minimum and maximum spray rates

From literature, the practical recommended minimum spray rate (to prevent whip-off of aggregate) for emulsions and hot conventional binders is 0.7 ℓ/m^2 (TRH3 2007). The maximum spray rate of an emulsion to prevent runoff is 1.5 ℓ/m^2 and 1.75 ℓ/m^2 for hot conventional binders (TRH3 2007). However, Muller, Sadler & Van Zyl (n.d.) state that these spray rates are only applicable to coarse textured surfaces on a relatively flat gradient. These authors recommend the following maximum application rates provided in Table 3.3.

Table 3.3: Maximum emulsion application rates for 65% emulsion (ℓ/m^2) (Muller, Sadler & Van Zyl n.d.)

Grade	Macro texture		
	<0.7 mm	1.0 mm	>2.0 mm
<4%	1.0	1.5	1.7
4-6%		1.0	1.3
6-8%			0.8

Note: “Grade” refers to the maximum gradient/cross-fall combination

Typical texture depths of selected seals are given in Table 3.4 below. These texture depths are typical for surfacing seals close to the end of their design life.

Table 3.4: Typical texture depths of selected seals (Van Zyl 2012)

Seal type	Texture depth (mm)
Fine slurry	0.2 – 0.4
Coarse slurry	0.4 – 0.7
9.5 mm single seal	0.7 – 1.5
13.2 mm single seal	0.7 – 2.2

Minimum spray rates for a double seal

TRH3 (2007) recommends the following minimum net cold binder (residual binder) application rates (see Tables 3.5 and 3.6).

Table 3.5: Minimum amount of net cold binder required for tack coat (TRH3 2007: Table 7-5)

Aggregate size	9.5 mm	13.2 mm	19.0 mm
Only construction traffic	0.5 ℓ/m^2	0.7 ℓ/m^2	1.0 ℓ/m^2

It is not recommended to accommodate traffic on the first layer. I f this is to happen, the next layer should be designed separately, as a second single seal (TRH3 2007).

Table 3.6: Minimum quantity of net cold binder required for penetration coat (with reference to double seal) (TRH3 2007: Table 7-4)

Aggregate size in top layer	4.75 mm or less	6.7 mm	9.5 mm
Minimum net binder required	0.3 ℓ/m^2	0.6 ℓ/m^2	0.7 ℓ/m^2

TRH3 (2007) notes that the above figures (in Tables 3.5 and 3.6) should be adjusted to hot spray rates and that the minimum hot spray rate should not be below 0.7 ℓ/m^2, in order to prevent whip-off of aggregate. To convert to hot spray rates, Table 7-3 of TRH3 (2007) is used. The term "hot" is used to refer to any type of binder, whether hot or cold applied binders like emulsions. Table 7-3 is reproduced as Table 3.7 on the next page. The minimum spray rates for the tack coat using cationic spray grade emulsion (65%) would therefore be as shown in Table 3.8.

From this table, the minimum binder application rate for a 19.0 mm seal is 1.550 ℓ/m^2. Since the maximum recommended spray rate is 1.5 ℓ/m^2, it implies that a 19.5 mm chip stone cannot be used in combination with spray grade 65% emulsion. Another combination of aggregate size-bitumen type would have to be chosen.

Table 3.7: Conversion from net cold residual binder to hot spray rates, spray temperatures and storage temperatures (TRH3 2007: Table 7-3)

Type of binder	Conversion *** factor	Spray temperature (℃)	Max. storage temperature (℃)
Cutback bitumen			
MC 3000	1.19 – 1.27	130 - 155	100
MC 70	1.63 – 1.72	60 - 80	Ambient
MC 30	1.88 – 1.99	45 - 65	Ambient
Penetration grade bitumen			
150/200 pen	1.09	145 - 185	115
80/100 pen	1.09	160 - 200	125
Polymer modified bitumen			
S-E1	1.08	165 - 190	150
S-E2	1.06	165 - 190	150
Bitumen rubber (S-R1)	1.07	195 - 205	-
Bitumen emulsions			
60% emulsion	1.68	60	Ambient
65% emulsion	1.55	60	Ambient
70% emulsion	1.44	70	Ambient

Table 3.8: Minimum quantity of hot binder required for tack coat

Aggregate size	**9.5 mm**	**13.2 mm**	**19.0 mm**
Only construction traffic	0.775 ℓ /m^2	1.085 ℓ /m^2	1.550 ℓ /m^2

3.3.3.2. Good practice

Muller, Sadler & Van Zyl (n.d.) recommend that the total net cold binder application rate for emulsions be divided into more than one application, whether a single seal or double seal is being used. For a single seal, it would be a tack coat (first application) and cover spray/fog spray/diluted emulsion (second application). For a double seal, it would be a tack coat, penetration coat and cover spray. This increases the area of aggregate in contact with the binder, thereby increasing bond strength (Muller, Sadler & Van Zyl n.d.). The effect of the emulsion cover spray is illustrated in Figure 3.1 on the next page.

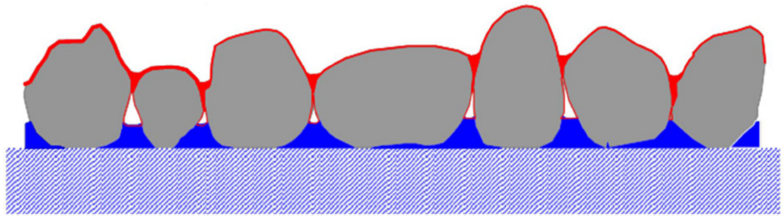


Figure 3.1: Bond between adjacent aggregate particles (Muller, Sadler & Van Zyl n.d.)

The amount of binder for each application is limited by the minimum application rates for each layer. If the application rate, when divided into two applications, becomes less than the minimum application rate, a cover spray may not be used.

It is also important to note that 'when splitting the binder into two applications, the second spray is normally applied at a higher rate than the first. This strategy reduces the run-off potential of the low viscosity emulsion' (Muller, Sadler & Van Zyl n.d, p.10).

3.3.3.3. Spray rate selection

The present study focuses on the final application rates decided upon by the Designer whether good practice is put into consideration or not. The choice of spray rates was therefore made without considering whether it was a tack coat, penetration coat or cover spray. The only consideration was that the spray rate be critical to a certain type of texture depth. This, however, did not include prime coats, because a bitumen emulsion does not usually seep through the pores of a finished base course (Jenkins 2012a). Bitumen droplets are kept to the surface by the attraction of the emulsifier and aggregate. If the existing base is porous, TRH3 (2007) recommends pre-treating the base with a diluted emulsion or applying a sand seal to choke the voids in the surface.

It was, however, found that testing with consistent spray rates and gradients would make the analysis simpler, as like-terms would be compared. This would also allow interpolation between intermediate values.

3.4. Flow chart of tests

With the above key aspects considered, a flow chart of the tests performed was developed by the researcher. This is illustrated in Figure 3.2.

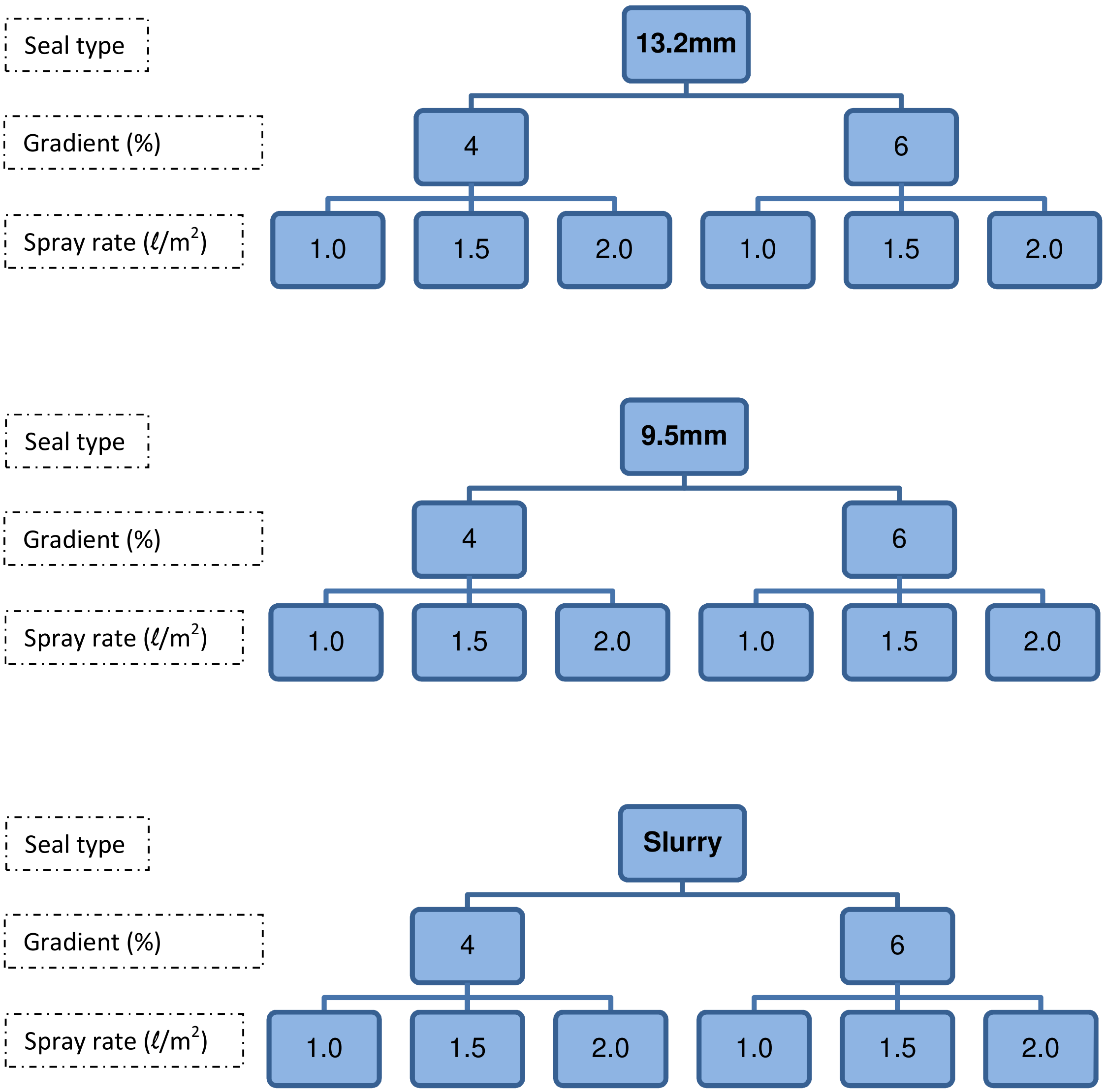


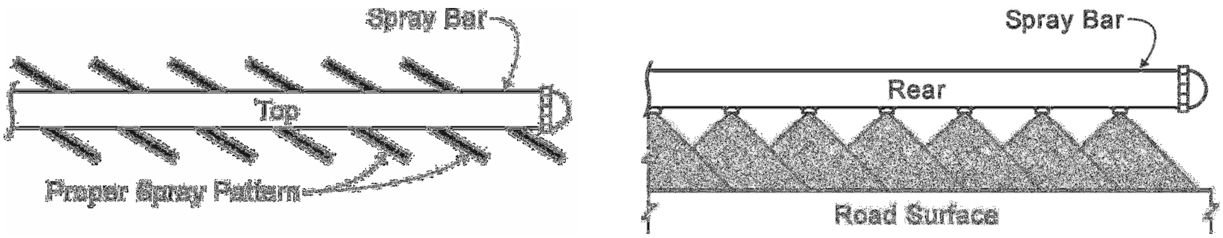
Figure 3.2: Flow chart of tests

3.5. Considerations during spray applications

A number of factors were considered to ensure that the binder would be sprayed according to standard practice. These factors include:

3.6.1. Spray pattern of the nozzles

Bitumen spray nozzles are designed to spray a fan-shaped pattern, rather than a circular spray (TxDOT 2010). The appearance of the fans as viewed from the top and rear of the distributor is shown in Figures 3.3a and 3.3b, respectively.



a) b)

Figure 3.3: View of distributor bar as seen from the (a) top and (b) rear respectively (TxDOT 2010)

The nozzles must be set to the proper angle. This is done so that the spray from each nozzle does not interfere with the flow from adjacent nozzles. The angle is usually between 15°-30°, depending on the manufacturer (Transportation Information Centre 1992; and TxDOT 2010). Distin (2008a) suggests an angle of 30°. An illustration of the nozzle setting is shown in Figure 3.4. All nozzles must be adjusted to the same angle to avoid a distorted spray pattern, which would lead to streaking (Transportation Information Centre 1992; and TxDOT 2010).

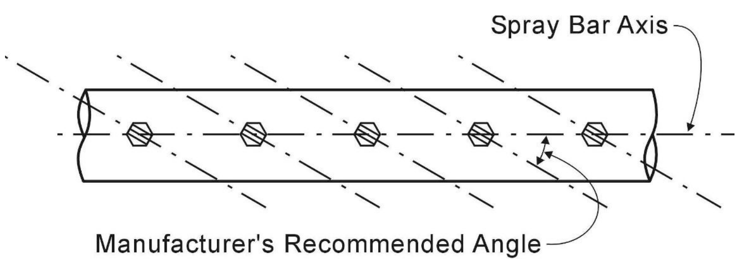


Figure 3.4: Nozzles on spray bar set at manufacturer's recommended angle (TxDOT 2010)

In order to achieve the correct fan width, the height of the spray bar above the road surface should be adjusted. Triple lap coverage is desirable (see Figure 3.5 on the next page) and is achieved at a spray bar height of 30.48 cm (TxDOT 2010) or a nozzle height of 24 cm (Distin 2008b).

The height of the spray bar above the road surface can be calculated using the following formula:

(Louw 2012)

Where: = spray bar height (mm)

= nozzle spacing (mm)

= nozzle angle to spray bar axis (degrees)

= fan angle of the nozzle (degrees)

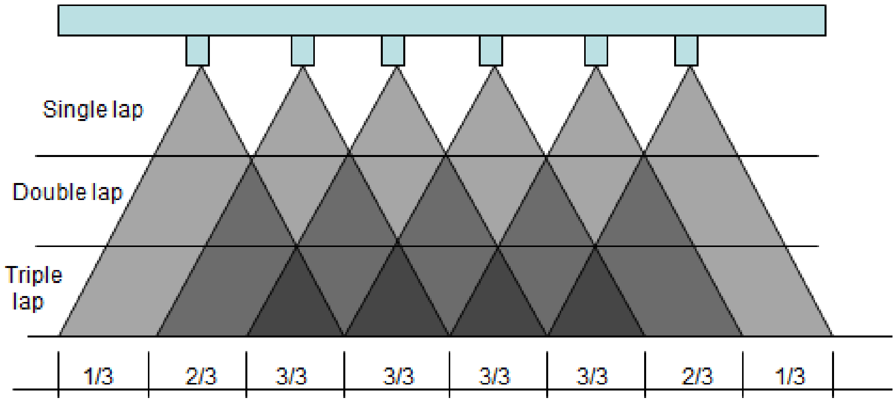
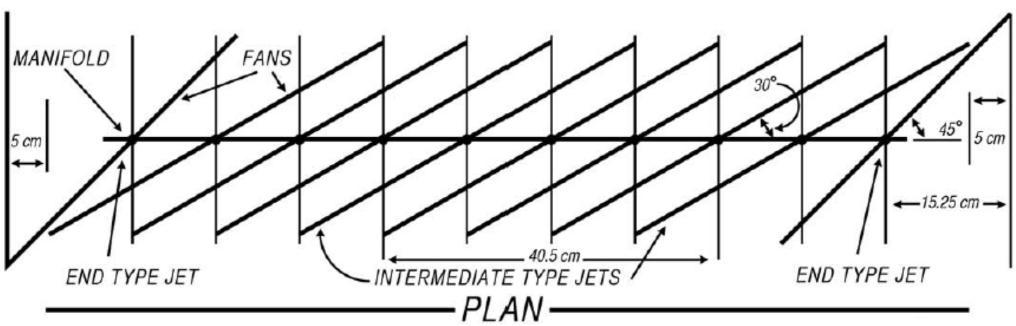


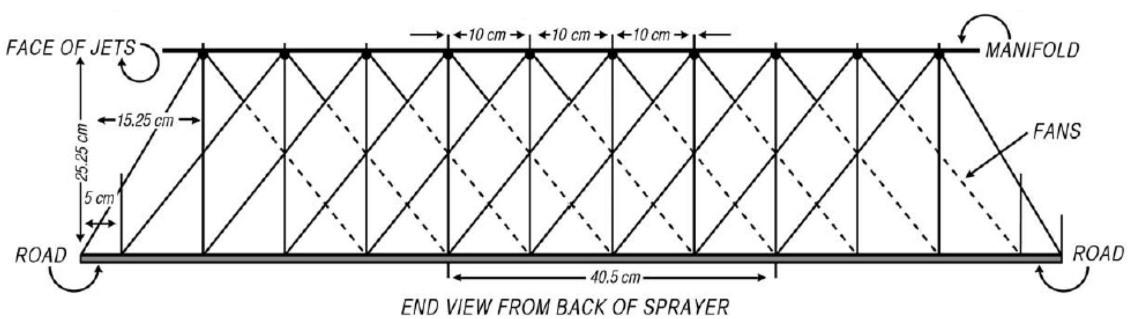
Figure 3.5: Spray patterns (Louw 2012)

For a nozzle spacing of 100 mm, nozzle angle of 30° and fan angle (flare angle) of 80°, the spray bar height would be 206 mm, and less than this for a nozzle angle less than 30°.

A E Copley Enterprises Pty Ltd (n.d.) provides the information illustrated in Figure 3.6 regarding nozzle angle, spacing and fan width.



a)



b)

Figure 3.6: Fan width after adjustment to 30 degrees: a) plan view and b) end view (A E Copley Enterprises Pty Ltd n.d.)

A closer examination reveals that the fan width, as viewed from the back of the distributor (Figure 3.6b), is shorter than the 40.5 cm stated in the figure. This is illustrated diagrammatically below in Figure 3.7.

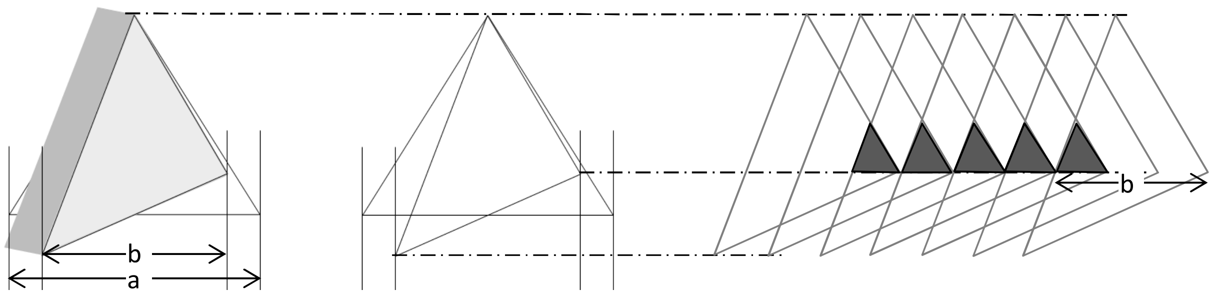


Figure 3.7: Fan width reduction due to rotation of the fan: a) initial dimension and b) adjusted dimension (diagram drawn by researcher)

Due to adjustment of the nozzles, the fan is rotated, resulting in a less width, as viewed perpendicularly from the back of the truck. From calculations, the perpendicular fan width would be approximately 30 cm (40cos30^o = 34.6 cm). 30^o is the nozzle adjustment, as shown in Figure 3.8 below.

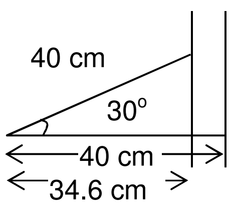


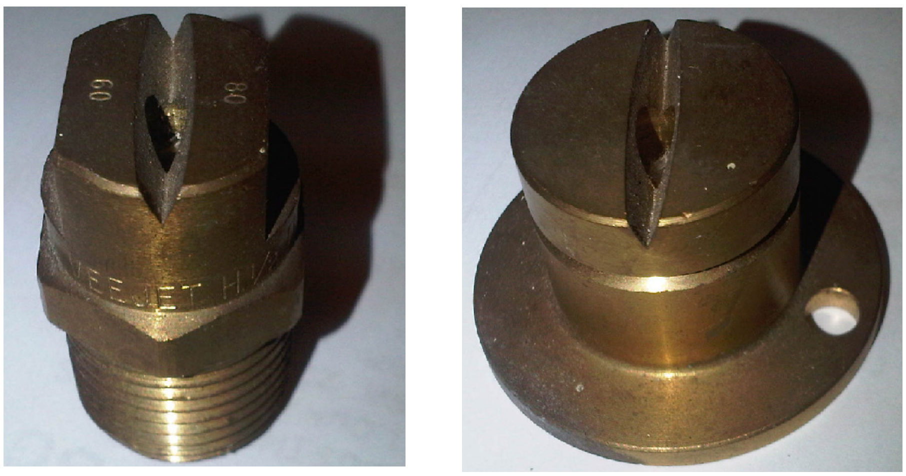
Figure 3.8: Computation of width reduction due to rotation (plan view)

Figure 3.7 also shows that the triangle shown in Figure 3.6 would not be isosceles, and that the fan angle would be reduced from 80^o to approximately 70^o.

The Arizona Department of Transport, ADOT (2008, p.404-4) states that an incorrect height of spray bar also causes streaking. If the spray bar is too high, the sprayed binder is subjected to wind, causing spotty coverage. ADOT (2008, p.404-4) recommends that the spray bar height should not vary by more than 12 mm along the width of the road, so as to obtain uniform coverage.

3.6.2. Type of nozzles used

The most common types of spray bar systems include: Bearcat, Etnyre, Rosco and Acmar (Distin 2008b). These spray bars are mostly 4.2 m in length and have nozzles spaced at 100 mm intervals (Distin 2008a). A typical Etnyre/Bearcat sprayer nozzle is shown in Figure 3.9 (a) below. The size of this nozzle is 80/60 (flare angle of 80^o). It has an outflow of approximately 150 litres per minute per meter length of the spray bar (Distin 2008a; and Louw 2012). The information on the side of this nozzle is: S.S.CO VEEJET H½U. The French Acmar machines use the nozzle type shown in Figure 3.9 (b). The hole on the base is a locating hole to ensure that the nozzle is mounted at an angle of 30^o to the spray bar (Louw 2012). This nozzle type also has a throughput of approximately 130-170 litres per minute per meter of the spray bar (Louw 2012).



a) **b)**

Figure 3.9: Nozzle types used on bitumen distributors: a) Etnyre/Bearcat sprayer nozzle and b) French Acmar sprayer nozzle (Louw 2012)

The nozzle type used in the current study is that shown in Figure 3.10 below. Information on the top of the nozzle is COLOR JET 80-8R, where 80 represents the fan angle in degrees, and 8R the size of orifice. From physical measurement, it has an internal orifice length of 3 mm and internal width of 1.5 mm. The information on the side of the nozzle is DELAVAN.

Figure 3.10: Nozzle type used in the current study (third photo adapted from Delavan Ltd, n.d.)

A E Copley Enterprises Pty Ltd (n.d.) produces a range of intermediate and end nozzles. The end nozzles produce double the amount of discharge produced by intermediate nozzles. Intermediate nozzles have the following specifications outlined in Table 3.9 below.

Table 3.9: Nozzle sizes and discharge rates produced by A E Copley Enterprises Pty Ltd (n.d.)

Nozzle number	Orifice width (mm)	Discharge rate (ℓ/min)
B8	4.44	36.36
B6	3.81	27.27
AN18	3.37	18.18
A3	2.92	13.63
S2	2.31	9.09
S1	1.56	4.54

A E Copley Enterprises Pty Ltd (n.d.) states that nozzle AN 18 is commonly used for general spraying of roads, and S2 for hand spraying of footpaths and other applications. The size of nozzle selected generally depends on the following factors (A E Copley Enterprises Pty Ltd n.d.):

i. The average rate of application of liquid to the surface (litres per square metre);
ii. The average forward speed of the vehicle used;
iii. The width of the spray bar; and
iv. The capacity of pump to supply.

3.6.3. Pressure at the nozzles

In order to achieve the desired discharge rate, the pressure at the nozzle should be approximately 82.73 kPa (A E Copley Enterprises Pty Ltd n.d.). The pressure must never drop below 68.94 kPa, because below this pressure, the fan and discharge from each nozzle would not be correct (A E Copley Enterprises Pty Ltd n.d.). Depending on the viscosity of the material being sprayed, the pressure of the pump may be altered to achieve the desired discharge.

> *As there is a considerable drop in pressure between the pump outlet and the nozzle orifice due to bends, restrictions and friction in the supply line, a considerably higher pressure is required at the pump outlet to maintain the correct pressure in the spray bar.*
> *A typical example from a test shows that for a 6 metre spray bar to provide an 82.73 kPa pressure at the nozzle, the pump outlet pressure is required to be approximately 275.79 kPa* (A E Copley Enterprises Pty Ltd n.d, p.13).

In this study, the author rounded off the 275.79 kPa to 300 kPa, considering the lengths of hose pipes used and the anticipated drop in pressure. This resulted in a discharge per nozzle of 3.2 ℓ/min. It was realized that the sprayed bitumen coming out of the nozzles appeared to be lighter in colour than that observed from presentations, in the literature and videos. The researcher concluded that this lightness was due to the use of smaller sized nozzles, and also because an emulsion was being sprayed rather than plain bitumen, which may have been the binder being sprayed in photos. Whereas an emulsion is brownish and less viscous, plain bitumen is black and more viscous. Larger nozzles were not used in this study because the spray bar available, used in a previous Masters project (de Vos 2007), already had the 80-8R fitted and there was no reason to suspect that the size was incorrect until the lightness of the fans raised doubt. Nevertheless, this was not important as long as the correct amount of bitumen/spray rate was achieved for the given discharge of the nozzles used. This correct amount of bitumen (spray rate) was achieved by controlling speed of the conveyor (see Section 3.4.3.5).

3.6.4. The bucket test

The bucket test is used to determine whether the spray nozzles are functioning properly; that each nozzle is spraying within the correct tolerance. In this test, a container is placed under each nozzle to catch all the flow from that nozzle (TxDOT 2010), as shown in Figure 3.11. The pump pressure is set and the sprayer turned on until the containers are approximately three quarters full (TxDOT 2010).

Figure 3.11: Calibration of a bitumen distributor spray bar (TxDOT 2010)

For surface treatments, the variation in weight between each bucket should not be more than 10% (TxDOT 2010).

According to South African practice, a bucket is placed under each set of three spray nozzles, as illustrated in Figure 3.12 below. The sprayer is then turned on for 15 seconds, and the net weight of binder in each bucket determined (Distin 2008a).

Figure 3.12: Calibration of binder distributor using the bucket test (Distin 2008a)

Table 3.10 provides the tolerances used with the bucket test.

Table 3.10: Tolerances for the bucket test (Distin 2008a)

Type of binder	Typical viscosity at spray temperatures	Maximum variation from the mean
Penetration, cutback or bitumen emulsions	40 – 100 cP	+-5.0%
Polymer modified binders	120 – 200 cP	+-7.0%
Bitumen rubber binders	2000 – 3000 cP	+-10.0%

In the bucket test, the mean of the buckets on the right hand, middle and left is determined. The maximum allowable variation between the mean of the right hand and the left hand should be less than 5.0% from the mean of the middle section (Distin 2008a).

Spray bar evaluation using the bucket test in the laboratory

In the laboratory, a bucket test was conducted by the researcher using water (see Figure 3.13 on the next page). In addition to the buckets and spray bar, a 30 ℓ bitumen container and an air compressor were used. The air compressor was used to provide the desired pump pressure. The results obtained are provided in Table 3.11 on the next page.

Figure 3.13: Bucket test conducted by the researcher in the laboratory

Table 3.11: Bucket test results 1

Test 1						Test 2		
	Outflow, (ℓ)						Outflow, (ℓ)	
Bucket	**1st half of bitumen container**	**2nd half of bitumen container**	**Total outflow**	**Variation from mean, (%)**		**Bucket**	**The whole bitumen container**	**Variation from mean, (%)**
1	4.0	4.8	8.8	22.2		1	8.6	22.2
2	3.0	2.8	5.8	-19.4		2	5.8	-17.5
3	3.1	2.8	5.9	-18.1		3	5.8	-18.3
4	4.0	4.3	8.3	15.3		4	8.0	13.7
Total	14.1	14.7	28.8			Total	28.2	
Mean			7.2			Mean	7.0	

Mean of end buckets, (ℓ)	8.6	
Mean of middle buckets, (ℓ)	5.9	
Variation of end nozzles from mid nozzles, (%)	31.6	Considering 8.6 as the base value

The spray bar did not pass the bucket test, as both the variation of each bucket from the mean, and the variation of the mean of the end buckets from the mean of the middle buckets exceeded the 5% given in Table 3.10.

The nozzles of the end buckets were therefore blocked using discs (three nozzles both ends). A spray test with bitumen emulsion was conducted and it was observed that the emulsion leaked from one end (see Figure 3.14 on the next page).

Figure 3.14: Spray bar testing with emulsion (arrow shows point of leakage)

The spray bar was thoroughly cleaned and a maintenance operation carried out. It was observed that the orifices of the outlet valves in the spray bar were of slightly varying sizes (see Figure 3.15 below). These valves could not be traced on the local market, and so they had to be refitted into the spray bar. The bucket test was repeated with all the nozzles on. The results that were obtained are shown in Table 3.12 on the next page.

The same results were observed as before the maintenance. For both bucket tests (Table 3.11 and the first part of Table 3.12), there was a slight variation in outflow values between the middle buckets. For bucket test results 2, this variation was 4%, which was acceptable (see Table 3.10). If the end nozzles were to be blocked, the spray bar would be considered to perform satisfactorily. Also from Table 3.12, it was observed that if the main valve to the spray bar was half closed, one half of the spray bar would produce half the amount of flow. It was therefore ensured that this valve be opened to its maximum during the spray tests, to avoid errors

Figure 3.15: Outlet valves of the spray bar

Table 3.12: Bucket test results 2

Valve to spray bar fully open				
	Bucket			
	1	2	3	4
Outflow, (ℓ)	8	6.5	6.05	7.4
			6.28	-0.04
Valve to spray bar half-closed				
	Bucket			
	1	2	3	4
Outflow, (ℓ)	3.8	2.9	1.65	1.9
			1.76	2.00

3.6.5. Speed of the spray bar

In the field, the operators of bitumen distributors know the delivery rate of the nozzles (litres/minute), and can thus control the speed of the truck in order to obtain the specified spray rate (ℓ/m^2).

In the laboratory, the delivery rate of the nozzles was obtained by spraying a known amount of bitumen at the field pressure (3 bars at the outlet of the air compressor used). The time the bitumen container took to empty was noted. Speed was calculated as discharge (ℓ/s) divided by spray rate (ℓ/m). This formula was derived from the following formula for computing the speed of a bitumen distributor:

$v = \frac{9Q}{WA(1+c)}$ (ADOT 2008)

where:

v = road speed in fpm (feet per minute)

Q = spray bar output, gal per min

W = spray bar width, ft

A = application rate, gal per sq yd

c = expansion coefficient resulting from heating the binder.

$c = \frac{T-60}{30(100)}$ (ADOT (2008)

where

T = application temperature, ^{o}F.

Substituting for c: c = (140-60)/3000 = 0.0267, which may be taken as negligible. The “9” in the above formula is a conversion from sq yd to sq ft, as 1 yard = 3 feet. This formula reduces to speed = discharge, Q divided by (spray rate x spray width). It is denoted as Method A in this document. Alternatively, the distributor speed could be computed from speed = distance divided by time (Method B).

Table 3.13 below indicates the speeds for various spray rates.

Table 3.13: Speed of spray bar using 6 nozzles (Method A)

Volume of bitumen, (ℓ)	Time to empty cylinder, (s)	Q at 3 bars, (ℓ/s)	Spray rate, (ℓ/m^2)	Spray rate for a spray width of 0.8m, (ℓ/m)	Speed (=Q/spray rate), (m/s)
22	67.82	0.324	0.7	0.56	0.579
			0.8	0.64	0.507
			1.0	0.80	0.405
			1.5	1.20	0.270
			2.6	2.08	0.156

A fan width of 30 cm could not be observed for a nozzle angle of 30^o and spray bar height of 30.5 cm above the spray surface. The fan width obtained constantly was 20 cm. The spray width for 6 nozzles was therefore 0.8 m.

It was realised that if an adequate amount of runoff was to be captured, the spray width had to start almost close to one end of the spray board and span a considerable width across the board. The nozzles were therefore increased from 6 to 10. This was assumed not to largely affect the bucket tolerance previously obtained as the largest orifices, as observed during the maintenance of the spray bar, were at the two ends. The new speeds that were used are shown in Tables 3.14 and 3.15 on the next page.

To achieve the above speeds in the laboratory, a speed controller (see Figure 3.16 on page 82) was installed so that the speed of the motor could be controlled accurately. The whole setup of the conveyor, speed controller and motor is shown in Figure 3.17. The speed controller used was a DELTA high-performance VFD-E Series AC motor. Though the latter is referred to as a motor, the term “motor”, as used in this document, was reserved for the motor shown in Figure 3.17.

Table 3.14: Speed of spray bar using 10 nozzles (Method A)

Volume of bitumen, (ℓ)	Time to empty cylinder, (s)	Q for 6 nozzles, (ℓ /s)	Q for 10 nozzles, (ℓ /s)	Spray rate, (ℓ/m^2)	Spray rate for a spray width of 1.2m, (ℓ/m)	Speed (=Q/spray rate), (m/s)	Frequency, (Hz)	Measured time over 3 m	Measured time over 1.5 m
22	67.82	0.324	0.541	0.7	0.84	0.644			
				0.8	0.96	0.563	29	5.36	2.68
				1.0	1.2	0.451	22	6.85	3.43
				1.5	1.8	0.300	15	10.34	5.17
				2.0	2.4	0.225	11.8	13.18	6.59

Table 3.15: Speed of spray bar using 10 nozzles (Method B)

Volume of cylinder, (m^3)	Time to empty cylinder, (s)	Q at 3 bars, for 6 nozzles, (m^3/s)	Q at 3 bars, for 10 nozzles, (m^3/s)	Spray rate, (ℓ/m^2)	Amount of bit required, (ℓ)	Amount of bit required, (m^3)	Time it takes to spray board (Area=1.5m*1.2m)	Speed = Distance/time, (m/s)
0.022	67.82	0.000324	0.000541	0.8	1.44	0.00144	2.66	0.563
				1.0	1.8	0.00180	3.33	0.451
				1.5	2.7	0.00270	4.99	0.300
				2.0	3.6	0.00360	6.66	0.225

Figure 3.16: Speed controller used to control the speed of the motor

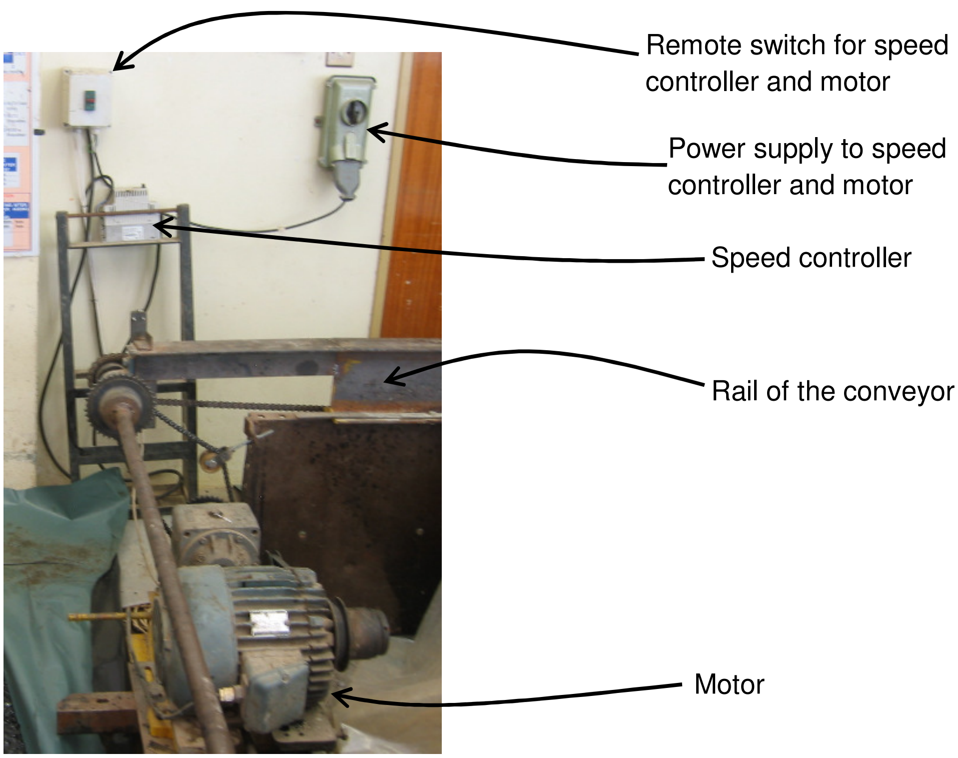


Figure 3.17: General setup of the conveyor, speed controller and motor

The setup of the conveyor system is shown in Figure 3.18 below. The motor on the conveyor system is for the operation of the compactor and is not the same as the motor in Figure 3.17. The connection of the spray bar is illustrated in Figure 3.19.

The motor had a wheel that was used to vary the speed of the conveyor but it was not possible to determine the exact speed directly without first calculating this from the distance and time. In preparation for the spray tests, the wheel was rotated to maximum so that it could easily be noticed that this speed setting had not been tampered with. The resulting speed was then controlled from the speed controller.

Speed control was obtained by adjusting the frequencies displayed by the speed controller. To determine which speed corresponded to which frequency, the time taken for the conveyor to travel through a specified distance was obtained. From this, the speed in m/s was calculated. The frequencies in Table 3.14 on page 81 were obtained for this experiment.

Figure 3.18: Front and back view of the conveyor setup

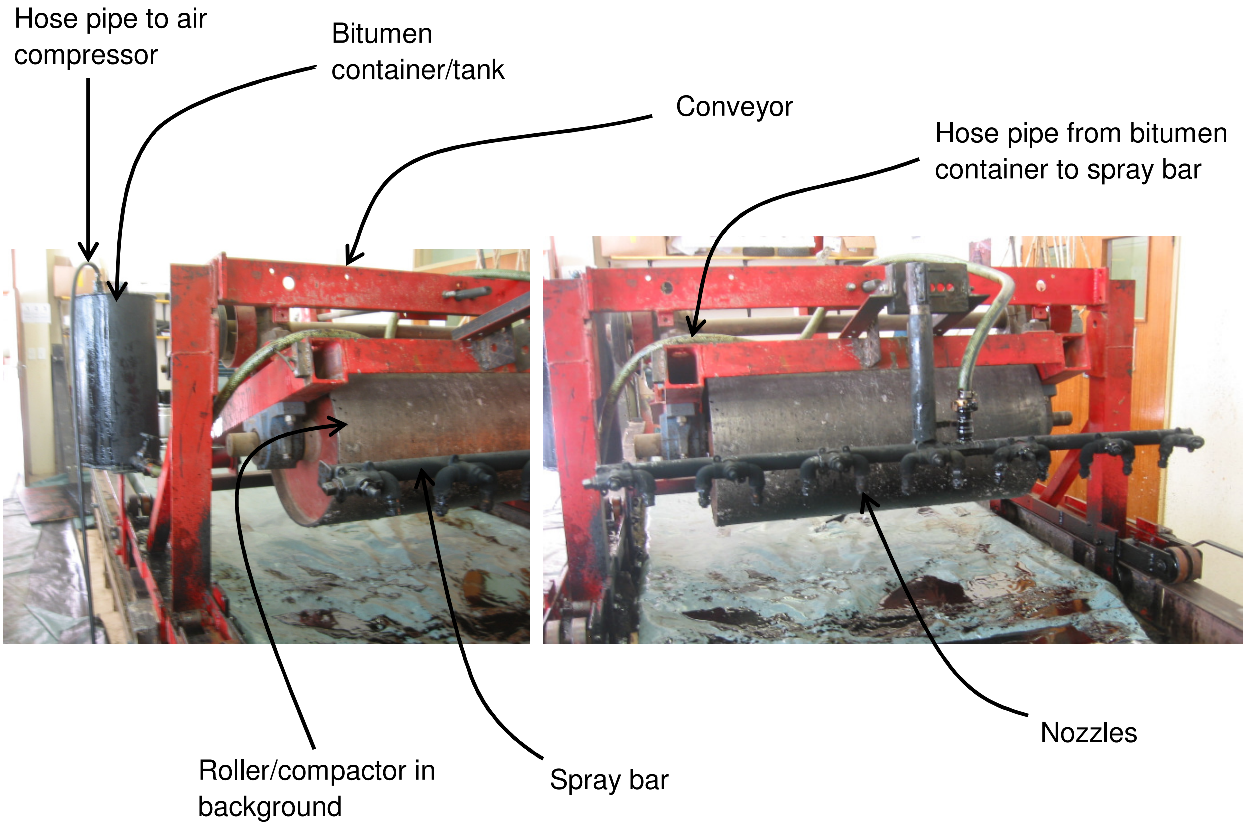


Figure 3.19: Spray bar and connections

3.6. Construction of surfacing seals

3.7.1. Aggregate spreading and compaction

Another key consideration in surfacing seal construction, besides the binder spray rate, is the aggregate spread rate. Gransberg & James (2005) state that aggregate spread is meant to ensure that a single layer of chip stones is applied, without excess. When the spread rate is not achieved, either excess chip stones are deposited or large portions of the binder are left uncovered. This would result in wind shield damage and pick up of the binder by construction vehicles, respectively (Gransberg & James 2005).

Aggregate spreading is following by compaction, but before the initial roller pass, the surface is swept to remove excess chippings that may have been deposited. The seal is usually compacted using a pneumatic tyred rolled immediately after laying the chip stones (Rizzutto 2008). Steel wheeled rollers are not used as these may crush the aggregate. Read & Whiteoak (2002) state that compaction is used to enhance the contact between the aggregate and the binder and also to enable the creation of interlock between the aggregate. In addition, rolling/compaction rolls the aggregate to its average least dimension, thereby preventing the aggregate from sticking out.

Transportation Information Centre (1992) states that the seal surface is properly constructed if the binder covers 2/3 of the aggregate height.

3.7.2. Construction of the 13.2 and 9.5 mm seals

To begin with, a platform (Figure 3.20 below) was fabricated and placed in the conveyor trough so that it could raise the spray board off the trough surface. The platform thus provided space to place the gutters that would be used to collect runoff when the run-off tests commenced. The top of the platform surface was made such that it could be tilted to various elevations using wedges.

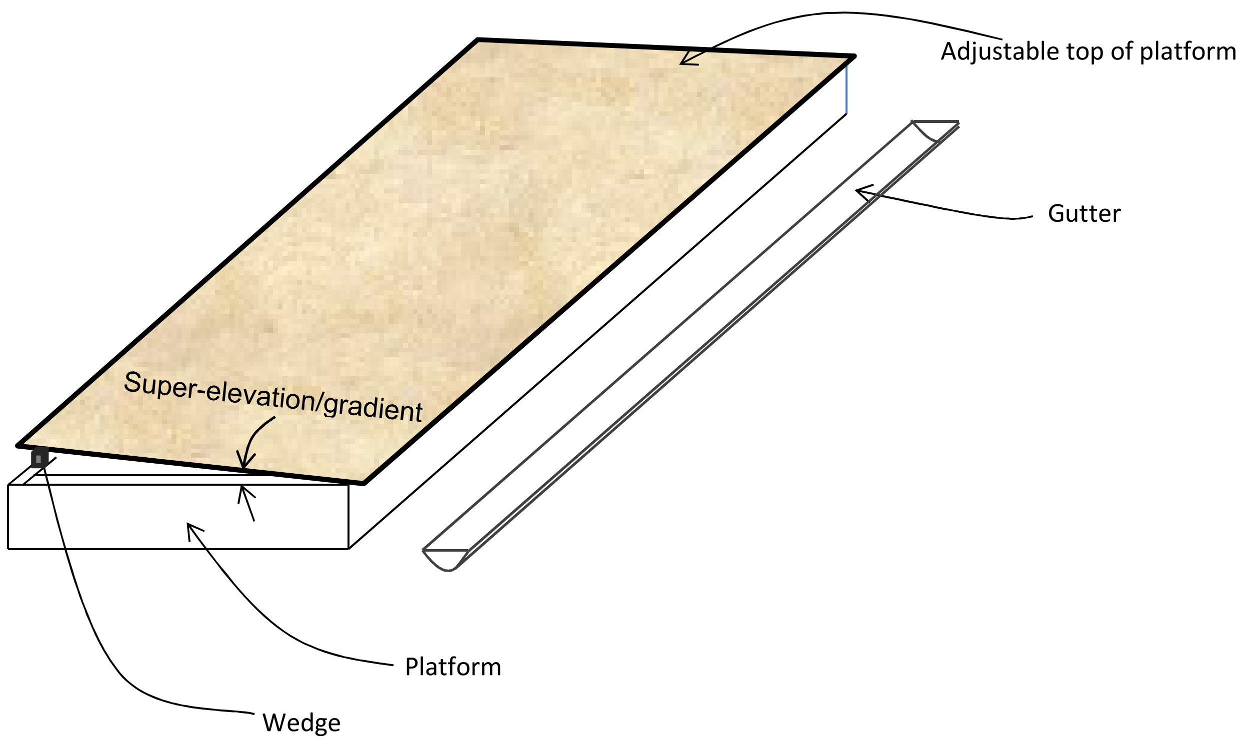


Figure 3.20: Platform on which the spray boards were placed

The spray board was placed onto the platform and an emulsion sprayed at a rate of 1.5 ℓ/m^2 using the spray bar. Aggregate was immediately spread onto the emulsion, starting from one end and progressing to the other. The TRH3 (2007) recommended spread rate for aggregate (computed at an estimated average of 110 m^2/m^3 for both seals) was not observed because the aggregate was being spread manually. It was difficult to control how much was being deposited per square metre. Aggregate that happened to be deposited in lumps could not be distributed/spread using a broom because this tended to roll the aggregate, thus bringing the binder to the surface. The surface was therefore swept the following day.

Since the aggregates were spread manually, the seal developed a dense shoulder-to-shoulder matrix and some stones were sticking out. The seal was therefore heated to soften the binder and compacted using a hand tamper. To avoid crushing of the aggregate, a rubber sheet was placed on top of the seal (see Figure 3.21 below). Although there was no space into which the stones could orientate, compaction reduced the extent to which they were sticking out, as illustrated in Figure 3.22.

Figure 3.21: Compaction of the seal

Figure 3.22: The 13.2 mm seal after compaction

3.7.3. Sand patch test

A sand patch test (SANS 3001-BT11) was conducted on the seals and the results showed that the seal macro texture (texture depth) was far from the texture depth of seals observed on site (see Sand patch test 1 in Tables 3.16 and 3.17). This texture depth was modified to field values by spraying several layers of emulsion.

After a series of sprays, it was apparent that the sides of the seals had not received the same quantity of binder. This was due to fan overlap variation, as shown in Figure 3.23 on page 90. The sides of the seals were sprayed manually and the binder spread using a brush. The final texture depth of seal ready for the run-off test was as shown in Figure 3.24. The sand patch test results are provided in Tables 3.16 and 3.17.

Table 3. 16: Sand patch test results for the 13.2mm seal

13.2mm seal	Diameter (cm)							
	D1	D1	D3	D4	Average D	S_{TD} (mm)	Average S_{TD} (mm)	Reduction
Estimated texture depth (from literature):						0.7-2.2	1.5	
Tack coat spray (1.5 ℓ/m2) and chip stones								
Sand patch test 1	8.0	10.9	9.5	8.7	9.3	7.4	7.4	
Cover spray 1 (1.5 ℓ/m2)								
Sand patch test 2	10.7	9.2	10.7	9.5	10.0	6.3		
Sand patch test 3	9.9	11.1	10.2	10.5	10.4	5.9	6.1	1.3
Cover spray 2 (1.5 ℓ/m2)								
Sand patch test 4	11.9	12.7	11.3	12.9	12.2	4.3	4.3	1.8
Cover spray 3 (3 ℓ/m2)								
Sand patch test 5	15.9	16.6	18.1	18.1	17.2	2.2		
Sand patch test 6	20.2	19.4	20.2	17.5	19.3	1.7	1.9	2.3
After run-off spray tests								
Sand patch test 7	26.0	20.2	25.0	22.5	23.4	1.2		
Sand patch test 8	21.5	20.7	18.4	22.1	20.7	1.5	1.3	0.6

Note: Surface texture depth is calculated using the formula:

$S_{TD} = 1273 \times \left(\frac{V}{D}\right)$ (SANS 3001-BT11:2012), where

S_{TD} = Surface texture depth (mm)

v = volume of sand (mℓ)

D = Average diameter of circular patch (mm)

v was taken as 50 mℓ.

Table 3. 17: Sand patch test results for the 9.5mm seal

9.5mm seal	Diameter (cm)							
	D1	D1	D3	D4	Average D	S_{TD} (mm)	Average S_{TD} (mm)	Reduction
Estimated texture depth:						0.7-1.5	1.1	
Tack coat spray (1.5 ℓ/m2) and chip stones								
No sand patch test not done					_	_	_	
Cover spray 1 (1.5 ℓ/m2)								
Sand patch test 1	11.3	11.9	11.7	11.1	11.5	4.8	4.8	
Cover spray 2 (1.5 ℓ/m2)								
Sand patch test 2	12.5	14.3	13.0	14.6	13.6	3.4	3.4	1.4
Cover spray 3 (3 ℓ/m2)								
Sand patch test 3	23.9	23.0	24.0	23.4	23.6	1.1		
Sand patch test4	19.9	20.0	20.1	21.0	20.3	1.6	1.3	2.1
After run-off spray tests								
Sand patch test 5	32.2	30.1	29.8	31.0	30.8	0.7		
Sand patch test 6	29.3	28.8	28.0	25.6	27.9	0.8	0.7	0.6

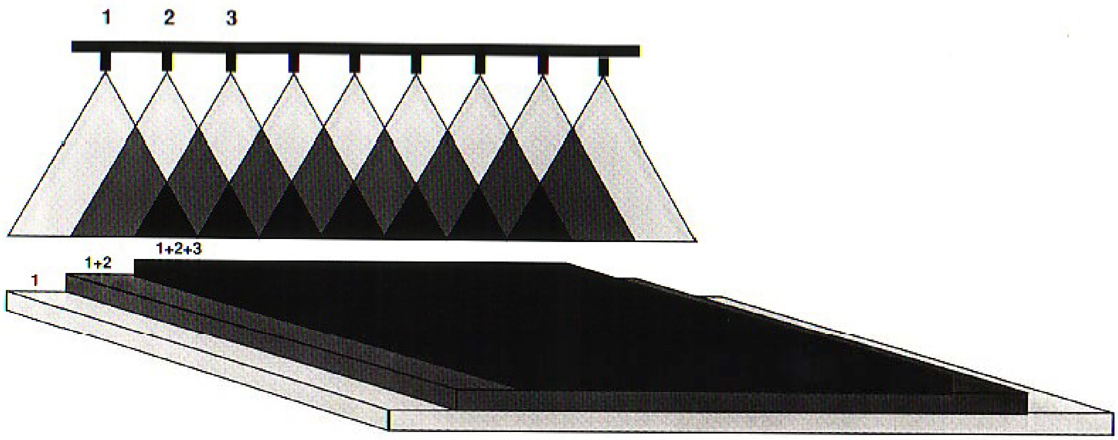


Figure 3.23: Binder distribution as a result of fan overlap (adapted from Jenkins 2011)

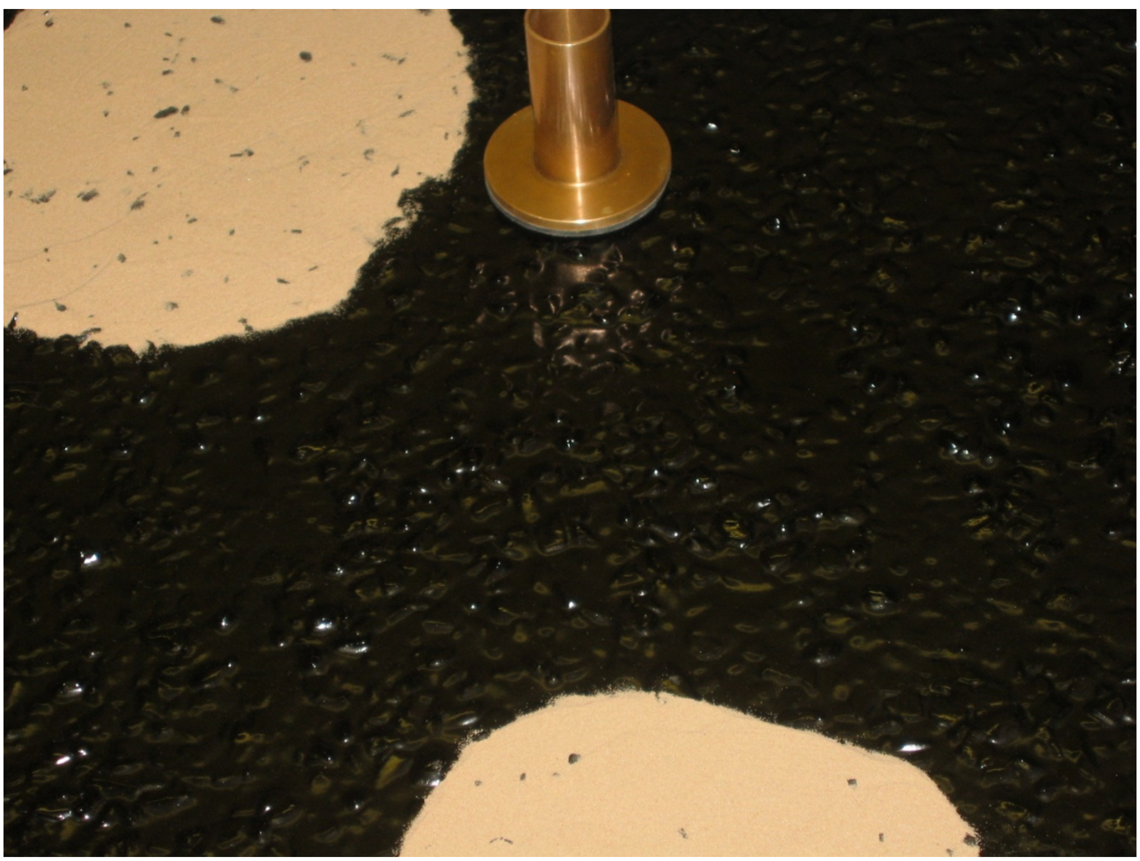


Figure 3.24: Sand patch test on the 9.5mm seal after the final layer of emulsion

3.7.4. Construction of the slurry seal

The aim of this section of the project was to construct a slurry seal/micro-surfacing.

3.7.4.1. Introduction

Gransberg (2010) states that although there is no significant difference between a slurry and micro-surfacing, the two can be distinguished as follows: A micro-surfacing is a mixture of cationic polymer modified bitumen emulsion, 100% crushed aggregate, water and other additives correctly proportioned and spread over a prepared surface. A slurry seal, on the other hand, is a mixture of aggregate, bitumen emulsion, water and additives correctly proportioned, mixed and spread over an adequately prepared surface. Slurry seal is applied in a mono-layer (Asphalt Institute 2008; and Gransberg 2010). 'A mono-layer is considered one stone thickness (based on the largest stone in the gradation) spread on the pavement surface' (Gransberg 2010, p.7).

Micro-surfacing is differentiated from slurry seals by the following three features, (Gransberg 2010):

i. Micro-surfacing always contains polymers;
ii. It cures rapidly through chemical reaction, which permits diverted traffic to be returned in a shorter time; and
iii. It can be placed in layers thicker than one stone deep.

i. Aggregate for the construction of a slurry

TRH3 (2007) states that aggregate used in the manufacture of slurries usually consists of crusher sand or a blend of crusher sand and natural sand. Furthermore, the amount of natural sand should not be more than 50% by mass of the aggregate blend, unless a cationic bitumen emulsion is used or an adhesion agent added.

The grading of aggregate for use in slurry seals is given in Table 8-5 and Table 8-6 of TRH3 (2007) for conventional and rapid setting slurries, respectively. Conventional slurries use unmodified bitumen emulsion whereas rapid setting slurries use modified emulsions. Table 8-6 was used in this study and is reproduced on the next page (see Tables 3.18). Table 8-5 in combination with Table 7-2 in TRH3 could also have been used. Table 7-2 provides a guide on the emulsion content of conventional slurries. Table 8-6 was used because it was more convenient, as there was no need to estimate the emulsion content, and the fact that the slurry could set quickly. The column for a nominal maximum aggregate size of 4.75 mm was used.

Table 3.18: Aggregate grading for rapid setting slurry (TRH3 2007: Table 8-6)

Sieve size (mm)	Nominal Maximum Aggregate size (mm)			
	4,75	6,7	9,5	13,2
	OVERLAYS		RUT FILLING	
	Cumulative percentage passing			
13,2	100	100	100	100
9,5	100	100	100	80-100
6,7	100	100	66-100	60-84
4,75	100	70-100	57-75	50-70
3,35	80-100	50-75	48-85	44-62
2,36	64-80	46-60	42-56	38-57
1,18	40-55	32-47	28-43	28-43
0,600	27-38	20-34	18-30	18-33
0,300	14-24	10-22	10-20	10-20
0,150	9-18	7-16	7-14	7-14
0,075	5-15	5-10	5-10	5-10
Sand Equivalent	35 min			
Modified emulsion	200 ℓ/m^3	190 ℓ/m^3	160 ℓ/m^3	150 ℓ/m^3

ii. Additional constituents

Cement or lime is always added to all slurries because it acts as a catalyst to keep the mix consistent and to improve the flow and workability of the slurry (TRH3 2007). The cement thickens the emulsion so that it does not flow off the aggregate causing segregation of the mix. The type of cement used with slurries is not important (Louw 2012). Louw (2012) states that:

> *When using anionic emulsions, the CaO in the cement hydrolyses to form $Ca(OH)_2$. The calcium ions react with the emulsifier system and form a thickening of the emulsion. In the case of cationic emulsions, the $Ca(OH)_2$ causes a change in the pH of the emulsion from about 2 to about 11, which is accompanied by thickening or gelling of the emulsion. COLAS has found that the degree of thickening varies somewhat depending on the grade of cement used, but that general thickening occurs in all cases, irrespective of the cement used* (Louw 2012).

The amount of cement or lime added is usually 1-2%. If the dust content[9] is greater than 7%, a 1.5% filler is added (TRH3 2007, p.77&88).

As a guide, the amount of water added is approximately 160 litres per cubic meter of dry aggregate (TRH3 2007, p. 72).

Three percent of polymer solids by mass of bitumen is regarded as the minimum amount of modifier to be added (TRH3 2007, p.73). In the current study, 3% latex (SC-E1) was used.

[9] Dust content refers to fines with a particle size less than 0.075 mm.

3.7.4.2. Blending and mixing

The blending and mixing of the slurry was performed according to the steps described below.

i. The amount of aggregate required for the mix was calculated. The following steps were taken:
   a. The volume of seal was computed as = 1.5 m x 1.22 m x 0.0048 m = 0.00878 m^3 (1.5 m was the length of the seal, 1.22 m the width and 0.0048 m the height. Although the maximum aggregate size was 0.00475 m, the height of mould[10] that could be made was 0.0048 m).
   b. If 1 cubic meter of dry aggregate weighed 1600 kg, 0.00878 m^3 would weigh (1600 x 0.00878) = 14.05 kg. In order to have sufficient amount for contingency, a blending for 20 kg was considered.
ii. Blending was carried out, as illustrated in Table 3.19 below.

Table 3.19: Aggregate quantities used in blending

Sieve size (mm)	Cumulative percent passing	Percent retained	Quantity of material to be included in a 20 kg sample, (g)
4.75	100		0
3.35	100	0	0
2.36	72	28	5600
1.18	47.5	24.5	4900
0.6	32.5	15	3000
0.425 (not considered by TRH3 (2007, p.117). See Table 3.18 on preceding page)			
0.3	19	13.5	2700
0.15	13.5	5.5	1100
0.075	10	3.5	700
Bottom pan	0	10	2000
Total		100	20000

Since the 0.425 mm sieve size was used, the researcher halved the amount required for the 0.3 mm sieve and apportioned it to the 0.425 mm sieve size. When blending, therefore, (2700/2) g was obtained from the 0.425 mm sieve size and (2700/2) g from the 0.3 mm sieve size. Two pans, each containing 10 kg, were used in order to obtain a thorough mixing.

iii. The slurry was mixed using the following amounts of constituents
   a. Cement: 1.5% of 20 kg = 0.3 kg of cement (see Section 3.4.5.1(ii) above).

[10] Mould, here, refers to formwork.

b. Water: In order to obtain the amount of water required, the following steps were undertaken:

i. The volume of the graded crusher dust was obtained by measuring the mixing container diameter and height up to where the levelled surface of the aggregate stopped. The following measurements were obtained:

Pan 1: Average diameter = 40.93 cm (from three readings, i.e. 40.4 cm, 41.4 cm and 41.0 cm); average height = 6.83 cm (from three readings, i.e. 6.0 cm, 7.0 cm and 7.5 cm).

Pan 2: Average diameter = 41.07 cm (from three readings, i.e. 41.3 cm, 41.3 cm and 40.6 cm); average height = 6.5 cm (from three readings, i.e. 6.5 cm, 6.5 cm and 6.5 cm).

ii. The volume of the aggregate was computed:

Volume of aggregate = $\pi\left(\frac{d}{2}\right)^2 h = 3.14 \times \left(\frac{0.4093}{2}\right)^2 \times 0.0683 = 0.00898m^3$ ……………Pan 1

Volume of aggregate = $\pi\left(\frac{d}{2}\right)^2 h = 3.14 \times \left(\frac{0.4107}{2}\right)^2 \times 0.065 = 0.008618m^3$…………….Pan 2

iii. Given that 1 m^3 of aggregate required 160 ℓ of water;

For Pan 1, 0.00898m^3 of aggregate required 1.437 ℓ of water.

For Pan 2, 0.00861m^3 of aggregate required 1.377 ℓ of water.

c. Emulsion: 200 ℓ/m^3 of emulsion was used (see Table 3.18), and therefore:

For Pan 1, 0.00898m^3 of aggregate required 1.796 ℓ of emulsion.

For Pan 2, 0.00861m^3 of aggregate required 1.721 ℓ of emulsion.

TRH3 (2007, p.75) recommends the following procedure for filling the mixer:

a) Aggregate is put in first.

b) Active filler is added slowly, care being taken to ensure that no lumps of cement/lime are added. Mixing continues until a uniform mix of aggregate and filler is obtained.

c) Water is added until the particles have been coated with water – there should be no dry fines in the mix. If this is done efficiently, the risk of balling of the mix is avoided.

d) Lastly, the emulsion is added. It may be prudent to dilute this emulsion before it is introduced to the mixer.

e) If necessary, water is added to obtain the required consistency.

The resultant slurry should be a smooth, creamy, uniform free-flowing mix, free of lumps and balling (TRH3 2007, p.75).

Following the above procedure, a slurry was mixed, poured onto the board and spread using a squeegee. A metal straight edge spanning past the edges of the formwork was used to level the slurry. The straight edge was moved from one end to the other and back, to ensure a level top surface. The slurry was then left to cure. TRH3 (2007, p.77) states that a rapid setting slurry can accommodate traffic within 60 minutes of laying. This implied that tests on the slurry could be performed after this duration.

After the laid slurry had cured, its surface was examined. The laid slurry had come out rough, with a texture depth greater than the 0.2-0.4 mm that was expected (see Table 3.4 on page 65). The reason for this was that the large stone particles (i.e. the 4.75 mm size) had been dragged by the straight edge, causing large voids behind the stone. This occurred despite the formwork height being 4.80 mm (see Figure 3.25 below). Burlap[11] was not used (dragged) because it was not available.

Figure 3.25: First layer of slurry showing a coarse texture

To fill these voids, another fine slurry was mixed, excluding the particles retained on the 2.36 mm sieve (see Table 3.19 on page 93). A sand patch test was performed, and this revealed that the required texture depth had not yet been attained (see Table 3.20 on the next page). Modification of the slurry seal continued until the desired texture depth was obtained. Photographs of the progression of texture depth improvement are shown in Figures 3.26-3.28 on the following pages.

[11] Burlap is a coarse cloth made of jute or hemp. It has a number of uses, such as the making of sacks, upholstering of furniture and as a backing for carpets (Webster's New World College Dictionary 2010)

Table 3. 20: Sand patch test results for the slurry seal

Slurry seal	**Diameter (cm)**							
	D1	**D1**	**D3**	**D4**	**Average D**	**S_{TD} (mm)**	**Average S_{TD} (mm)**	**Reduction**
Estimated texture depth:						0.2-0.4	0.3	
Slurry seal surface (after Fill 1)								
Sand patch test 1	19.2	19.8	18.7	18.5	19.1	1.8		
Sand patch test 2	21.1	22.5	20.5	24.0	22.0	1.3	1.5	
After Fill 2								
Sand patch test 3	24.6	24.6	24.9	25.1	24.8	1.0		
Sand patch test 4	25.3	25.7	24.1	24.5	24.9	1.0	1.0	0.5
After Fill 3								
Sand patch test 5	40.2	41.1	41.5	38.0	40.2	0.4		
Sand patch test 6	39.8	35.5	38.6	40.8	38.7	0.4	0.4	0.1
After run-off spray tests								
Sand patch test 7	34.5	31.1	33.0	32.0	32.7	0.6		
Sand patch test 8	34.6	31.5	30.0	33.5	32.4	0.6	0.6	0.2

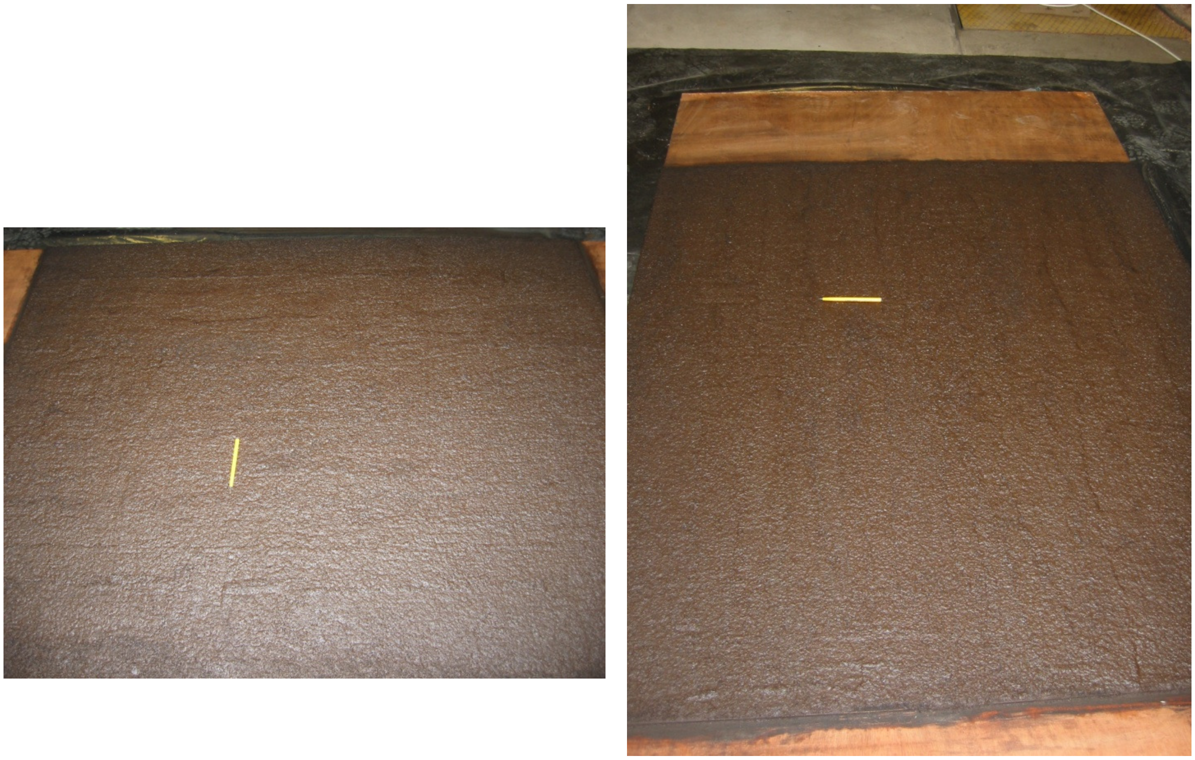


Figure 3.26: Second layer of slurry before this had cured

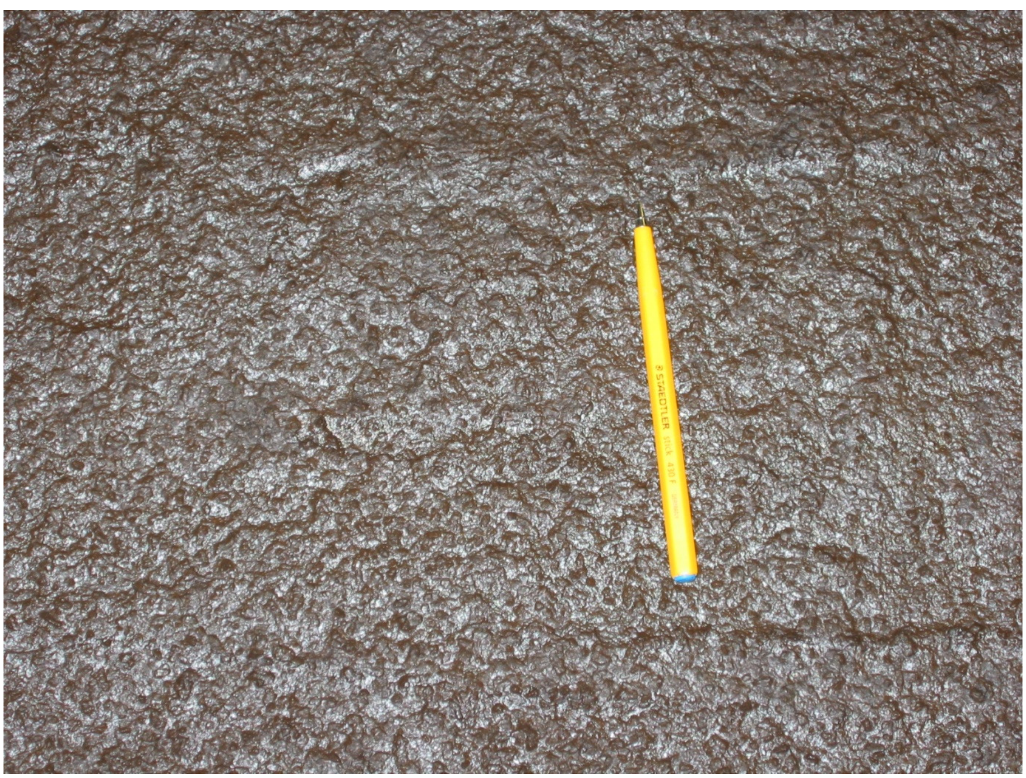


Figure 3.27: A close-up of the second layer of slurry before this had cured

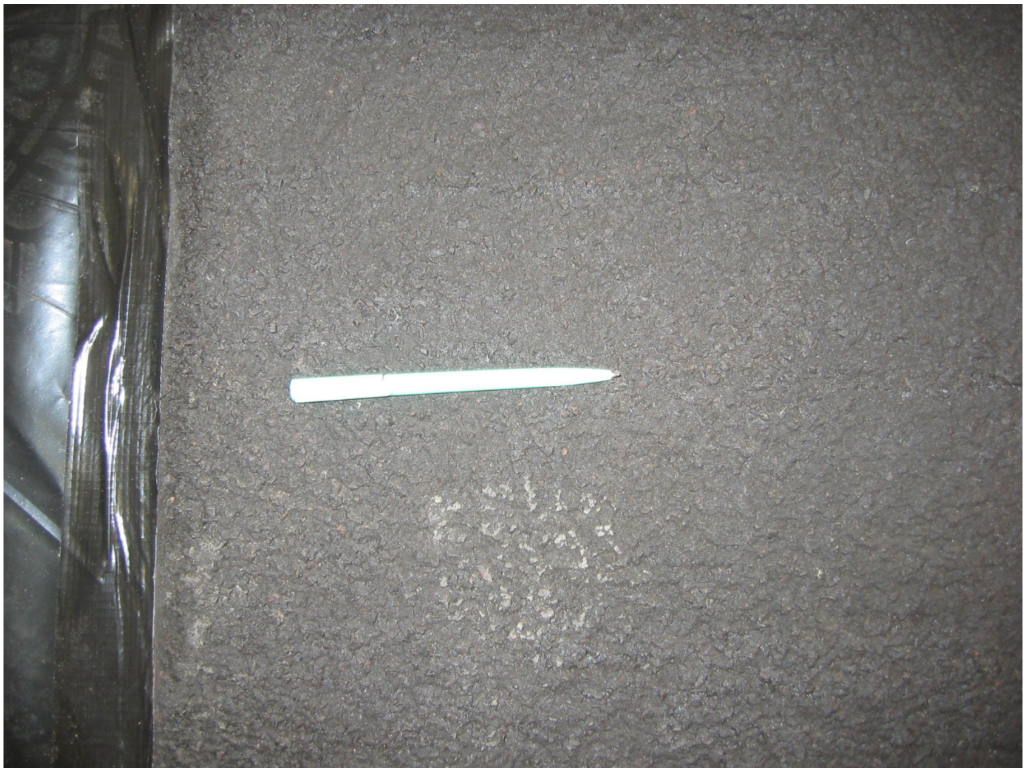


Figure 3.28: Fourth layer of slurry ready for run-off tests

Photos of the sand patch test are shown in Figures 3.29 and 3.30 below.

Figure 3.29: Sand patch test on the slurry after the second last fill (Fill2)

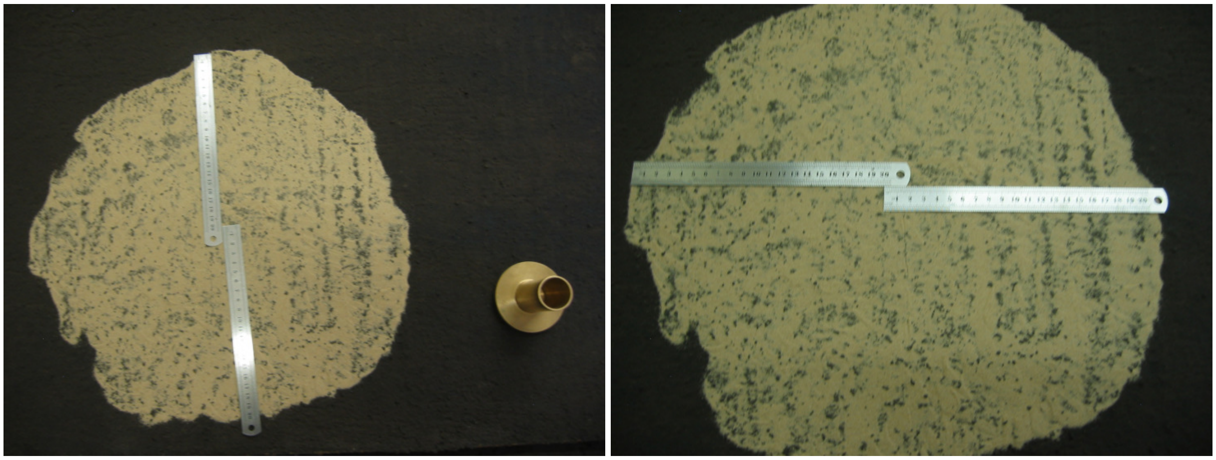


Figure 3.30: Sand patch test on the slurry after the last fill (Fill 3)

3.7. The run-off tests

For each of the three types of seals used (i.e. the 13.2 mm, 9.5 mm and slurry seal), the cationic spray grade emulsion was sprayed at 1.0, 1.5 and 2.0 litres per square meter. The amount of run-off was measured and the dynamics of the emulsion were also monitored (visually using paint diluted to the same viscosity as the emulsion).

3.8.1. Equipment used

The following equipment was used for the run-off test:

i. A bitumen container (bitumen tank, which was approximately 30 ℓ);
ii. Spray bar;
iii. Hose pipes (used to connect the bitumen container to the spray bar, to collect the emulsion from gutter and direct it to the measuring cylinder, and to wash the spray surface);
iv. Measuring cylinder (2000 mℓ);
v. Beakers (2000 mℓ, 400 mℓ and 100 mℓ);
vi. Stopwatch;
vii. Air compressor;
viii. Blow torch;
ix. Buckets;
x. Spanner;
xi. Screw driver;
xii. Oven;
xiii. Thermometer; and
xiv. The conveyor system

3.8.2. Sequence of activities

The sequence of activities was as follows:

i. The sample seal surface was lifted onto the platform, and elevated to the desired gradient using wedges.

ii. The bitumen container containing emulsion at 60^{o}C, the spray temperature, was removed from the oven and mounted onto the conveyor system. Once the emulsion was used up, the bitumen container was refilled in-place with standby emulsion stored at 70^{o}C in the oven. During the process of refilling, the emulsion temperature dropped to the spray temperature. Temperatures were always confirmed by measurement with a thermometer.

iii. In cases where the emulsion temperature dropped below 60^{o}C, the bitumen container was heated in-place using a blow torch (see Figure 3.31 on the next page). The blow torch was applied evenly and swiftly, to prevent heat concentrations. The bitumen container was not disconnected and placed in the oven as this would require re-cleaning the hose pipe and spray bar, and there would be a waste of emulsion in the hose pipe system. This is because at the connections, some bitumen emulsion usually spilled and smeared the faces of the fire hose couplings. This emulsion quickly broke and required heavy cleaning before the couplings could be reconnection, if these were to fit. It was also feared that the emulsion would break, coat the lining of the pipe and spray bar, and also block the nozzles while waiting for the bitumen container to heat up in the oven.

iv. The spray bar was heated so that the emulsion would not cool down and fail to pass through the nozzles. It was also heated in between sprays to melt the emulsion that had broken at the nozzles (see Figure 3.32 on the next page).

v. The sample seal surface was then sprayed. Figures 3.33 to 3.35 show the seal before, during and after spraying. The photo in Figure 3.34 (b) is more under-exposed than that in (a).

vi. As the emulsion flowed downstream, it was collected into the gutter, and from the gutter to the measuring cylinder (see Figure 3.36 on page 103). The amount that ran off was recorded.

vii. One litre of water was poured into the gutter to dilute the emulsion for a faster flow into the cylinder, and to wash the remaining emulsion out of the gutter. The latter was aimed at reducing the error in the measured run-off emulsion as a result of some remaining behind as coating to the gutter and outflow pipe.

viii. When the emulsion from the seal surface was just dripping (after approximately 8-11 minutes), the run-off measurements were stopped. The seal surface was immediately washed with water, and then blown with air to dry the surface (see Figure 3.37 (a) & (b) on page 104). If washing of the surface was delayed, the emulsion would break decreasing the texture depth of the seal and hence influencing the run-off results of subsequent tests.

ix. The spray bar was reheated and the next spray test performed.

Figure 3. 31: Bitumen container being heated using a blow torch

Figure 3.32: Spray bar being heated using a blow torch

Figure 3.33: Seal surface before spraying

a) b)

Figure 3.34: The spraying operation: a) valve to spray bar opened approximately 1 m away from the spray surface in order to allow the pressure at nozzles to equalise and hence produce a steady outflow, and b) spray bar passing over the seal surface

Figure 3.35: Seal surface after spraying

Figure 3. 36: Emulsion flowing into the gutter

a) b)

Figure 3.37: Cleaning the seal surface after a spray test: a) Seal surface being washed with water and b) Seal surface being blown with high air pressure

3.8.3. Challenges faced and troubleshooting

During the execution of the tests, a number of challenges were faced and troubleshooting was necessary. For repeatability in future research, the researcher has included these challenges and solutions (see Table 3.21 below). Most of challenges arose because there was no standard for test preparation and procedure. Experience was, therefore, attained with increasing tests conducted.

Table 3.21: Challenges faced during the spray tests

	Challenge	Solution
i.	The spray bar was old and had many maintenance issues	The spray bar was soaked overnight in diesel, and flushed three times with the same diesel at high pressure. The spray bar was also taken for maintenance, where the outlet valve handle was also removed because it was not functioning. The spray bar was then reassembled and the valves set to operate fully open without the handle
ii.	A drop in temperature of the emulsion was experienced with time during the day	The bitumen container was heated in-place with a flame
iii.	The bitumen container was heavy (made of heavy thick	Same as (ii) above

	metal) and therefore could not be disconnected every end of day such that it could be refilled and placed in the oven	
iv.	The nozzles were getting blocked often, i.e. after approximately 4-6 sprays	The assembly was dismantled, cleaned and reassembled, each time this happened. The spray bar was also heated each time before spraying.
v.	The emulsion could not drain completely out of the gutter and hose pipe, for the first spray test. This is because the hose pipe did not have sufficient slope to drain the collected emulsion	The gutter was cut so that it could be lifted easily without pouring the collected emulsion. The emulsion would then have sufficient slope to flow through the hose pipe to the measuring cylinder. It was not considered a viable solution to drill through the metallic trough, which contained concrete on which the platform and spray surface were resting. It would also require drilling through the concrete. Since tests had already commenced, cutting the gutter was the better solution. Results for this test were cancelled and the test was repeated
vi.	Fittings/accessories of one middle nozzle outlets broke during adjustment when it was discovered that the emulsion was leaking at that nozzle, during one of the tests	One of the end nozzle fittings were shifted to the middle nozzle and another stop-end (disc) fabricated for this end nozzle
vii.	As the bitumen container emptied, it sprayed a mixture of bitumen and air. This resulted in a spotty non-uniform binder thickness. The test in progress had to be discarded and repeated. This resulted in a waste of time since the spray surface had to be rewashed and	It was noted after how many sprays the bitumen container emptied, and refilled before the end of this count

	blown, and the test preparation procedure repeated.	
viii.	Due to obstacles such as tiny aggregate in the conveyor path (on the rail), the conveyor was stopped midway of the spray surface during one of the spray tests. Excess emulsion was deposited at this point as the conveyor stood still, though the valve to the spray bar had been closed in time. This test also had to be repeated, resulting in a waste of time.	It was ensured the rail was, at all times, clear of such obstacles.
ix.	There was a speed reduction due to sticky bitumen droplets deposited onto the rail of the conveyor, from previous spray tests.	This was noted during the texture depth modification of the seals, and it was ensured that the rail be cleaned every end of day.
x.	A variation in run-off per second results between repeats was noted after the first few tests. It was also noted that different spray rates took different durations for the emulsions to stop dripping off the seal surface. At first, a shorter duration (before the emulsion stopped dripping) had been chosen but this was discovered to give misleading results, if different spray rates were to be compared.	It was decided that timing be done up to when the emulsion was just dripping.
xi.	Tests were conducts on pavements at ambient temperature (23-25^{o}C) rather	Recommendation to consider maximum pavement temperature, in future research, was made.

	than the maximum pavement temperature experienced in South Africa. It was not feasible to achieve the desired pavement temperature with the equipment available.	

3.8. Ethical and environmental issues

Ethical consideration was given to the handling and disposal of waste bitumen and its solvents. Only the latter, however, was identified as a potential danger to the environment.

From the classification of hazardous wastes, bitumen is not flammable as its flash point is greater than or equal to 220^{o}C (Read & Whiteoak 2003). Valley Slurry Seal Co (2000) states that emulsions do not have a flash point. Bitumen is also not reactive or corrosive (pH 6-12) (Golder Associates Africa, GAA 2009). In the third edition of Minimum Requirement for the Handling, Classification and Disposal of Hazardous wastes by the Department of Water Affairs and Forestry - South Africa (DWAF 1998), four penetration grade bitumen samples collected from major manufacturing plants in South Africa passed as non-toxic to the environment (GAA 2009). South Africa therefore regards bitumen as non-hazardous. Read & Whiteoak (2003) state that bitumen is not only used in road construction, but also in roofing felts, reservoir linings and the internal lining of potable water pipes.

Read & Whiteoak (2003) report that research conducted by Shell (Brandt et al 1999; and Potter et al 1999) showed that bitumens are unlikely to penetrate the skin or be absorbed by the body, and that cutbacks are unlikely to cause a carcinogenic risk. Read & Whiteoak (2003) also note that the International Agency for Research on Cancer found that there was no direct evidence to associate bitumen with long-term skin disorders in humans. These authors, nevertheless, advise against prolonged skin contact with bitumen, and most especially bitumen emulsions, as the latter can cause irritation to the skin and eyes in some individuals.

Whereas bitumen is classified as non-hazardous (GAA 2009), mineral turpentine used to clean bitumen off equipment and surfaces is classified with a hazard rating of 2 (high hazard) (DWAF 2005). Its disposal is by incineration and landfill-ash blend, or recovery (recycling, reuse and utilisation techniques) (DWAF 2005). Turpentine is highly flammable; irritating to the skin (can cause contact dermatitis); may cause lung damage if swallowed;

may cause chemical pneumonitis[12], when inhaled, which can be fatal; and is toxic to aquatic life (SOS Oil Corporation 2008; and KCB Sales Pty Ltd 2010).

The turpentine and diesel used to clean the equipment in this study was recovered (reused), and at the end of the experiments safely disposed off into a specially designed container/tank outdoors, where it evaporated. This disposal method was considered not to pose danger because these solvents evaporate rapidly into the air. Incineration was not used because an incinerator was not available.

Tarpaulin was used to protect the work areas, and any spillage onto the tarpaulin was wrapped up and packed for disposal. The emulsion used for trial testing was collected back into its container for easy carting to spoil.

Finally, safety equipment was used and care was taken not to store the solvents close to flames.

3.9. Conclusion

Laboratory based tests were performed to determine the run-off at various combinations of variables. This was preferred to in-situ testing for the reasons stated in this section. Laboratory samples of seal surfaces were therefore constructed. A circular sand patch test was performed to confirm that the desired texture depth had been attained. It took a number of cover sprays/fills in order to attain this as shown by the test results. Spray tests were then performed. The latter required a lot of preparation before and in between tests and also involved manoeuvring heavy equipment and test samples.

The next chapter discusses the analysis of the results obtained.

[12] Pneumonitis is inflammation of the lungs (Webster's College Dictionary 2010)

Chapter 4 : Results and analysis

'Everyone is entitled to his own opinion but not his own facts' — Daniel Patrick Moynihan

4.1. Introduction

In this section, the run-off test results are evaluated. Procedural steps as shown in Figure 4.1 are taken. The work is described in three phases:

i. Phase 1: The runoff test results are introduced and discussed. The underlying methods of analysis are evaluated in order to identify the most suitable, depending on the capabilities and limitations of the method.
ii. Phase 2: The variables are evaluated and investigated on an individual basis. It is important to note that no statistical analysis is incorporated at this point as further statistical analysis in the last phase showed the interdependency of independent variables through regression analysis.
iii. Phase 3: This incorporates the statistical analysis of the variables tested.

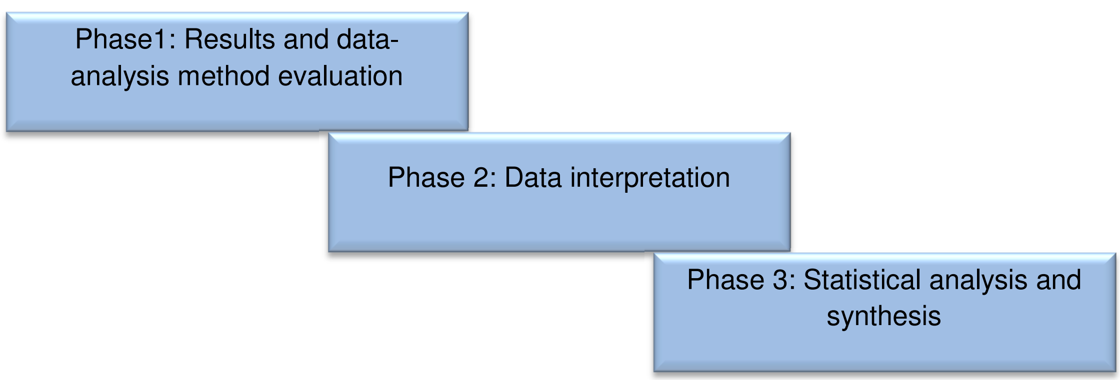


Figure 4. 1: Chapter organisation

4.2. Results and data analysis method evaluation

4.2.1. Run-off test results

This section discusses the results obtained from the run-off tests described in Chapter 3. These results are provided in Table 4.1 on the next page.

Table 4. 1: Runoff test results

Surfacing seal	Texture depth (mm)	Gradient (%)	Spray rate (L/m^2)	Amount sprayed (mL)	Runoff (mL)	Runoff (mL/m^2)	% Runoff	Duration (s)	Runoff (mL/s)
13.2 mm seal	1.6	4	1.0	1800	50	28	2.78		
	1.6	4	1.0	1800	50	28	2.78		
	1.6	4	1.5	2700	600	333	22.22		
	1.6	4	1.5	2700	820	456	30.37	730.80	1.1
	1.6	4	2.0	3600	1050	583	29.17		
	1.6	4	2.0	3600	800	444	22.22	62.25	12.9
	1.6	4	2.0	3600	1575	875	43.75	603.90	2.6
	1.6	6	1.0	1800	150	83	8.33	222.23	0.7
	1.6	6	1.0	1800	280	156	15.56	659.21	0.4
	1.6	6	1.5	2700	900	500	33.33	484.74	1.9
	1.6	6	1.5	2700	900	500	33.33	705.76	1.3
	1.6	6	2.0	3600	850	472	23.61	237.92	3.6
	1.6	6	2.0	3600	1700	944	47.22	785.88	2.2
9.5 mm seal	1.0	4	1.0	1800	140	78	7.78	650.76	0.2
	1.0	4	1.0	1800	170	94	9.44	642.37	0.3
	1.0	4	1.5	2700	340	189	12.59	519.60	0.7
	1.0	4	1.5	2700	600	333	22.22	596.43	1.0
	1.0	4	2.0	3600	1200	667	33.33	712.80	1.7
	1.0	4	2.0	3600	1330	739	36.94	674.45	2.0
	1.0	6	1.0	1800	380	211	21.11	475.05	0.8
	1.0	6	1.0	1800	220	122	12.22	512.87	0.4
	1.0	6	1.5	2700	920	511	34.07	766.09	1.2
	1.0	6	1.5	2700	1000	556	37.04	754.04	1.3
	1.0	6	2	3600	1300	722	36.11	854.86	1.5
Slurry seal	0.5	4	1.0	1800	320	178	17.78	846.97	0.4
	0.5	4	1.0	1800	150	83	8.33	626.19	0.2
	0.5	4	1.5	2700	1280	711	47.41	898.13	1.4
	0.5	4	1.5	2700	1040	578	38.52	621.67	1.7
	0.5	4	2.0	3600	2200	1222	61.11	723.49	3.0
	0.5	4	2.0	3600	1800	1000	50.00	852.32	2.1
	0.5	6	1.0	1800	200	111	11.11		
	0.5	6	1.0	1800	150	83	8.33		
	0.5	6	1.5	2700	650	361	24.07		
	0.5	6	1.5	2700	1450	806	53.70		
	0.5	6	2.0	3600	2120	1178	58.89		
	0.5	6	2.0	3600	2310	1283	64.17	551.09	4.2

The first column indicates the type of surfacing seal and subsequent columns indicate the texture depth in mm, gradient in %, spray rate in ℓ/m^2, amount sprayed in mℓ, runoff in mℓ, runoff in mℓ/m^2, percent runoff, duration and the runoff in mℓ/s, respectively. The average value of texture depth, i.e. average of value before run-off tests and value after all the run-off test, is used.

The 13.2 mm seal was the first to be tested and the runoff collected was recorded in mℓ. The gutter was removed when the emulsion was just dripping. After four sprays, the researcher thought that it would be a good idea to record runoff also in mℓ/s. It was thought that regardless of the amount collected, the runoff in mℓ/s would be consistent. The gutter was therefore removed early, at three occasions as highlighted in Table 4.1. It was later realised that there was a difference in the mℓ/s results between repeats, i.e. Reading 1 and Reading 2 (see challenge (x) in Table 3.18 of this document). From the comparison of these repeats, however, it was observed that most of the emulsion ran off during the first few minutes. The speed of runoff decreased with increase in time, implying that the flow was unsteady.

After studying the results of the 13.2 mm seal, timing was stopped and better means of handling the situation sought. During this period, spray tests on the slurry seal, at 6%, had begun. The gutter was removed when the emulsion was just dripping, similar to the first case. This explains the reason as to why the runoff in mℓ/s for the slurry is partly recorded. Timing was again resumed because rheology of the binder is time dependent and this would provide valuable reference in regard to understanding the binder behaviour at a particular time. Timing was, however, performed up to when the emulsion was just dripping and the gutter removed. A standard time for which to remove the gutter was not set because different spray rates take different time for the emulsion to stop flowing. The same applied to different gradients. The 9.5mm seal was the last to be tested.

Although results were recorded in mℓ/s, it was found more meaningful to record results also in mℓ/m^2. Recording results in mℓ/s would imply that runoff could be determined for any given time, which would present slightly inaccurate results. It was noted that the chip spreader usually lags behind the bitumen distributor by approximately 15-20 minutes (Louw 2012), this being the worst case. By this time, the emulsion would have stopped flowing as runoff occurs within the first few minutes. Computing runoff in mℓ/s over this time would therefore be incorrect.

4.2.2. Evaluation of the method of analysis

In this section, the method of analysis is discussed. However, as noted in Section 4.1, the behavioural response of the binder to the variables tested is provided in Section 4.3. A statistical analysis and the inference of the outcomes is provided in detail in Section 4.4.

Since run-off is dependent on a combination of factors, that is, texture depth, gradient and spray rate, it was found appropriate to use multivariate analysis. Multivariate analysis is the simultaneous analysis of two or more predictor/independent variables that influence the outcome of the dependent variable under investigation (Hair et al 2010). For this case, the independent variables were texture depth, gradient and spray rate; and the dependent variable was run-off.

Multivariate Analysis should not be confused with Multivariate Analysis Of Variance (MANOVA). MANOVA is defined as 'a statistical analysis used to assess the significance of the effect of one or more independent variables on two or more dependent variables. It is usually used when the dependent variables are thought to be intercorrelated' (Richarme 2001). Since the research has only one dependent variable, i.e. run-off, a MAVONA cannot be carried. A univariate analysis of variance was therefore performed. It is, however, noted that multiple regression can be performed. Multiple regression falls under multivariate analysis and is defined as a statistical technique that predicts a dependent variable based on multiple independent variables (Richarme 2001; and Princeton University 2012)

In the current study, multiple regression analysis was done using SPSS. Output values were confirmed with doing the same regression analysis in Microsoft Excel. It is important to note that Excel only outputs coefficients of a linear equation. For it to output nonlinear equation coefficients, the input data is first converted to the exponents of the desired equation. For example, if spray rate is cubed, the spray rate values are first cubed, and then fed into the data analysis tool as cubed values. If the desired nonlinear equation is unknown, Excel can be used. Statistical software like STATISTICA and SPSS is appropriate for this. The difference between SPSS and STATISTICA is that the latter has provision for programming making it close to an "open" type product (Marques de Sa 2003).

Understanding linear regression

The current scenario includes one dependent variable (runoff) and three independent variables (spray rate, gradient and texture depth). It is necessary to explain the theory of regression analysis, but would be cumbersome in this section to do it for the multiple variables at hand. The theory is, thus, explained by using only one independent variable.

The best-fitting curve to a given set of points can be determined using least squares. This is the minimum sum of the squares of the offsets ("the residuals") of the points from the curve. 'The sum of the squares of the offsets is used instead of the offset absolute values because this allows the residuals to be treated as a continuous differentiable quantity' (Wolfram Research, Inc. 2013).

Usually, vertical offsets are minimised instead of perpendicular offsets (see figure 4.2) because this is related to the generation of the fitted function, i.e. x estimates y. Use of vertical offsets also allows a change from best fit line to best fit polynomial (Wolfram Research, Inc. 2013).

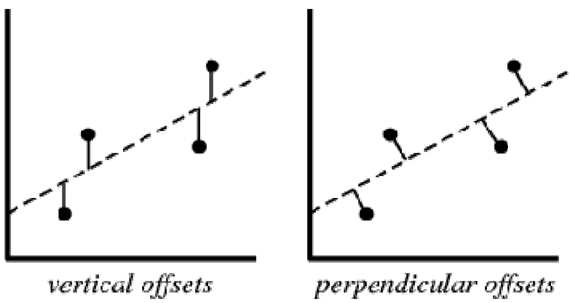


Figure 4. 2: Curve fitting to a number of points (Wolfram Research, Inc. 2013).

Vertical least squares fitting proceeds by finding the sum of the squares of the vertical deviations R^2 of a set of n data points from a function.

If the fitted function is described by $(\hat{x}_i, \hat{y}_i)$ and the data points from which it was fitted are (x_i, y_i), the resulting residual $R^2 = \sum_1^n (y_i - \hat{y}_i)^2$. In order to determine the best fit line, R^2 is minimised as follows: $\frac{d(R^2)}{dm} = 0$ and $\frac{d(R^2)}{db} = 0$ (for a linear equation $\hat{y} = m\hat{x} + b$, with each pair of offsets represented as $y_i = mx_i + b + R$, where m = slope of the fitted function, and b = $\hat{y}$-intercept). Substituting for R^2:

$$\frac{d(R^2)}{dm} = -2\sum_{i=1}^{n}(y_i - mx_i - b)x_i = 0$$

$$\frac{d(R^2)}{db} = -2\sum_{i=1}^{n}(y_i - mx_i - b) = 0$$

Solving these two equations, the coefficients m and b are found to be:

$m = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}$; $b = \frac{\sum_{i=1}^{n} y_i \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}$ (Wolfram Research, Inc. 2013)

The goodness of fit/correlation/strength of relationship of the equation, r-square is also found to be: $r^2 = \frac{(n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i)^2}{[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2][n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2]}$ (Wolfram Research, Inc. 2013)

The correlation coefficient, r ranges from +1 to -1, where +1 indicates a perfect positive correlation, -1 a perfect negative correlation and 0 no relationship. (Note that r = R).

The error between the actual vertical point y_i and the fitted point is given by:

$$e_i = y_i - \hat{y}_i$$

The estimator of variance in the e_i is given by $s^2 = \sum_{i=1}^{n} \frac{e_i^2}{n-2}$. The standard errors for m and b are given by: $SE(m) = \frac{s}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}}$; $SE(b) = s\sqrt{\frac{1}{n} + \frac{(\bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}}$ (Wolfram Research, Inc. 2013), where $\bar{x}$ = mean of n number of x's.

Analysis of variance

Analysis Of Variance (ANOVA) is a statistical technique for comparing means of three or more independent variables (Eckel 2008). This technique yields values that can be tested to determine whether a significant relation exists between variables (Princeton University 2012).

For the analysis of variance in a multiple regression, the following sums of squares are used:

i. Total sum of squares (SST): This is the total deviations in the dependent variable (Gupta 2000). It is computed as 'the sum of squared deviations between each observation and the overall mean (i.e. mean of means)' (Eckel 2008).

   $SST = \sum_{i=1}^{k} \sum_{j=1}^{n} {y_{ij}}^2 - \frac{\left(\sum_{i}^{k} \sum_{j=1}^{n} y_{ij}\right)^2}{Kn}$ (Wolfram Research, Inc. 2013), where

   n = number of replicates (sets of identical observations),

   K = number of factor levels (number of independent variables or treatment groups),

   y_{ij} = jth observation in factor level i

ii. Regression Sum of Squares/model sum of squares/Treatment sum of squares/explained sum of squares (SSR): This is the amount of the SST that can be explained by the model (Gupta 2000).

$SSR = \frac{1}{n}\sum_{i=1}^{k}\left(\sum_{j=1}^{n} y_{ij}\right)^2 - \frac{1}{Kn}\left(\sum_{i}^{k}\sum_{j=1}^{n} y_{ij}\right)^2$ (Wolfram Research, Inc. 2013)

iii. Error sum of squares/Residual Sum of Squares (SSE): This is the amount of the SST that cannot be explained (Gupta 2000).

$SSE = \sum_{i=1}^{k}\sum_{j=1}^{n}\left(y_{ij} - \bar{y}_i\right)^2 = SST - SSR$ (Wolfram Research, Inc. 2013), where $\bar{y}_i$ = mean of observations within factor level i .

From the sum of squares, the F-value is computed. This tests the global (overall) significance of the model (Davies n.d.). The larger the F, the more in the direction of significance (CSDN 2010).

F is computed as:

$F = \frac{MSR}{MSE}$, where

MSR = mean square value of treatments; and

MSE = mean square value of residuals.

These are computed and output as shown in Table 4.2 below.

Table 4. 2: ANOVA for global significance

Category	Sum of squares	Degrees of freedom (df)	Mean square	F-ratio
Model	SSR	$K-1$	$MSR = \frac{SSR}{K-1}$	$\frac{MSR}{MSE}$
Error	SSE	$K(n-1)$	$MSE = \frac{SSE}{K(n-1)}$	
Total	SST	$Kn-1$	$MST = \frac{SST}{Kn-1}$	

It could be argued that these explanations should be put in the literature review or methodology. The author felt that the use and appropriateness would be more effective in this chapter.

4.3. Analysing the factors that influence runoff

In this section, the variables that influence runoff are analysed individually. Graphical representation is used to interpret the runoff behaviour/response to the three variables. Statistical analysis follows in Section 4.4.

In order to analyse consistent results, runoff results in Table 4.1 were filtered to remove observations where the gutter was removed early. These observations are highlighted in red in Table 4.1. As can be seen from this table, runoff was collected after 3 minutes, which is approximately a third of the duration taken by other observations.

4.3.1. Influence of spray rate on runoff

Table 4.1 was rearranged into Table 4.2 on the next page and a plot of runoff versus spray rate made (see Figure 4.3 on page 118). New columns were introduced in Table 4.2 as indicated.

In Figure 4.3, considering the 13.2 mm seal and a spray rate of 1 ℓ/m^2, the amount of binder sprayed is 1000 $m\ell/m^2$ and this results in a runoff of 28 $m\ell/m^2$ at a gradient of 4%, and a runoff of 156 $m\ell/m^2$ at a gradient of 6%. At a spray rate of 1.5 ℓ/m^2, 1500 $m\ell/m^2$ are sprayed and this results in a runoff of 394 $m\ell/m^2$ at a gradient of 4% and a runoff of 500 $m\ell/m^2$ at a gradient of 6%. The graph may be interpreted the same for a spray rate of 2 ℓ/m^2. Since average values are plotted, the Y-error bar was used to represent the location of the actual runoff readings, i.e. Reading 1 and Reading 2. The upper point of the Y-error bar represents the higher of the readings, and the lower point represents the lower of the readings. Graphs for the average runoff for the 9.5 and slurry seals may be interpreted the same. The variation in Reading 1 and 2 was presumed to have been caused by a decrease in mechanical efficiency of the spray bar and/or a texture depth modification from the previous spray test. The phrase "mechanical efficiency" as used in this document describes how adequate the nozzles were functioning. With an increasing number of sprays, a decrease in discharge from the nozzles was experienced but this was visually unnoticeable. It was only when the decrease was noticeable that the spray bar was dismantled and the nozzles washed.

A colour code is used to differentiate between the seal types. Blue is used for the 13.2 mm seal, Green for the 9.5 mm seal and Red for the slurry seal.

From Figure 4.3, the following is observed:

- Runoff increases with increase in spray rate as expected
- There is a higher runoff at a gradient of 6% compared to 4%. There is an exception

Table 4. 3: Table arrangement for spray rate evaluation

Surfacing	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m^2)	Amount sprayed ($m\ell/m^2$)	Runoff reading 1 ($m\ell/m^2$)	Runoff reading 2 ($m\ell/m^2$)	Average runoff ($m\ell/m^2$)	% Average runoff	Increase in average runoff ($m\ell/m^2$)	Increase in average runoff (%) x100	Increase in % average runoff (%) x100
13.2mm seal	1.6	4	1.0	1000	28	28	28	2.8	0		
	1.6	4	1.5	1500	333	456	394	26.3	367	13.20	8.47
	1.6	4	2.0	2000	583	875	729	36.5	335	0.85	0.39
	1.6	6	1.0	1000		156	156	15.6	0		
	1.6	6	1.5	1500	500	500	500	33.3	344	2.21	1.14
	1.6	6	2.0	2000		944	944	47.2	444	0.89	0.42
9.5mm seal	1.0	4	1.0	1000	78	94	86	8.6	0		
	1.0	4	1.5	1500	189	333	261	17.4	175	2.03	1.02
	1.0	4	2.0	2000	667	739	703	35.1	442	1.69	1.02
	1.0	6	1.0	1000	211	122	167	16.7	0		
	1.0	6	1.5	1500	511	556	533	35.6	367	2.20	1.13
	1.0	6	2.0	2000	722		722	36.1	189	0.35	0.02
Slurry seal	0.5	4	1.0	1000	178	83	131	13.1	0		
	0.5	4	1.5	1500	711	578	644	43.0	514	3.94	2.29
	0.5	4	2.0	2000	1222	1000	1111	55.6	467	0.72	0.29
	0.5	6	1.0	1000	111	83	97	9.7	0		
	0.5	6	1.5	1500	361	806	583	38.9	486	5.00	3.00
	0.5	6	2.0	2000	1178	1283	1231	61.5	647	1.11	0.58

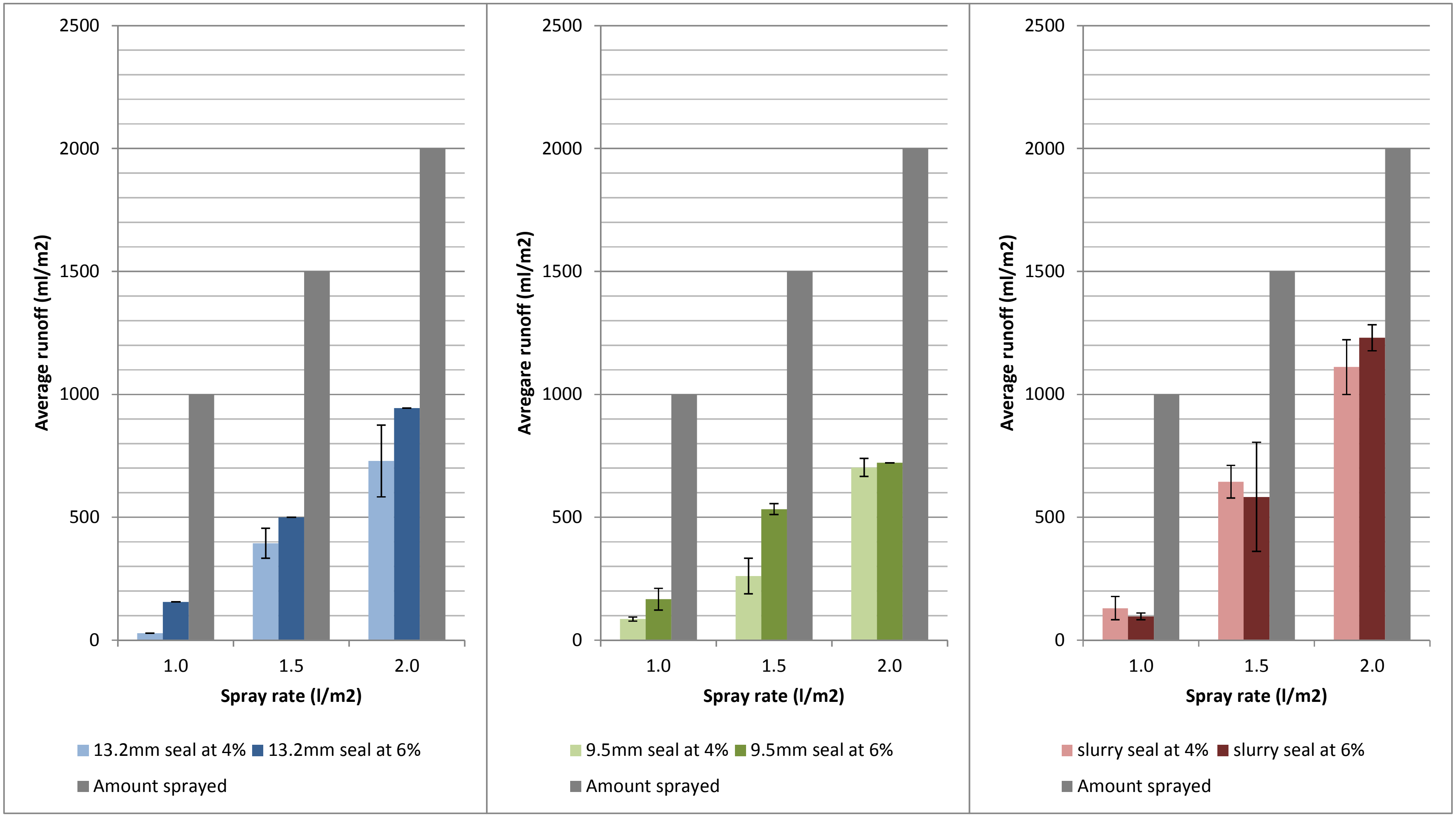


Figure 4. 3: Average runoff versus spray rate for the 13.2 mm, 9.5 mm and slurry seal respectively

for three observations on the slurry seal at 6%. One probable reason for this is that the gutter could have been removed a little earlier than for the case of 4% where timing was done (see Table 4.1). The other probable reason is that there could have been a problem with the mechanical efficiency of the spray bar. The last probable reason is that emulsion was sprayed onto a fresh surface (of aggregate-emulsion-cement) and this provided a greater attraction of the runoff emulsion. Subsequent runoff tests were conducted on the same surface but this contained adhered emulsion (from preceding tests) that could not be completely washed off. One would expect more runoff on bitumen coated aggregate.

Note that the increase in runoff from 1 to 1.5 ℓ/m^2 and from 1.5 to 2 ℓ/m^2 cannot be compared. The reason for this is that before the binder starts to run off (i.e. for spray rates of 0 to 0.5 ℓ/m^2), there is adsorption. As the spray rate increases, the adsorption lessens. The spray rate of 1 ℓ/m^2 was probably still being affected by adsorption as it was observed that this spray rate took a longer time to start flowing compared to 1.5 ℓ/m^2. A spray rate of 2 ℓ/m^2 took the shortest time to start flowing. It is therefore inappropriate to compare the run-off of 1 ℓ/m^2 spray rate with the next increment.

The combined graphs of average runoff versus spray rate are provided in Figures 4.4 and 4.5.

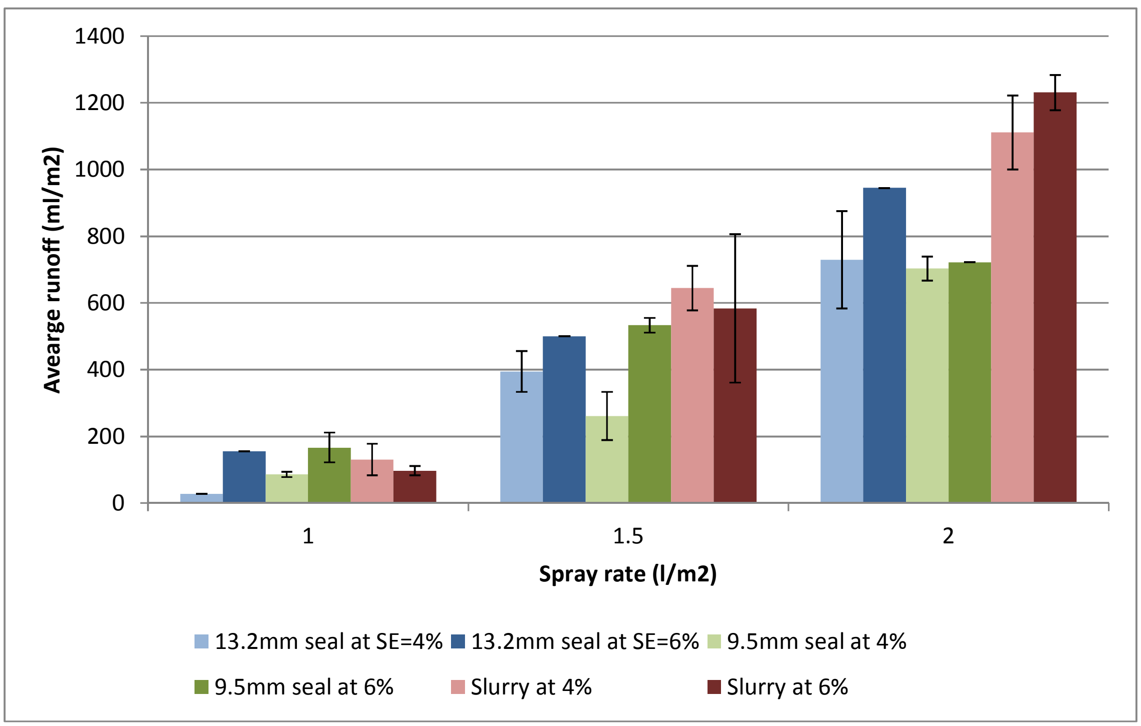


Figure 4. 4: Average runoff versus spray rate (combined Graph 1)

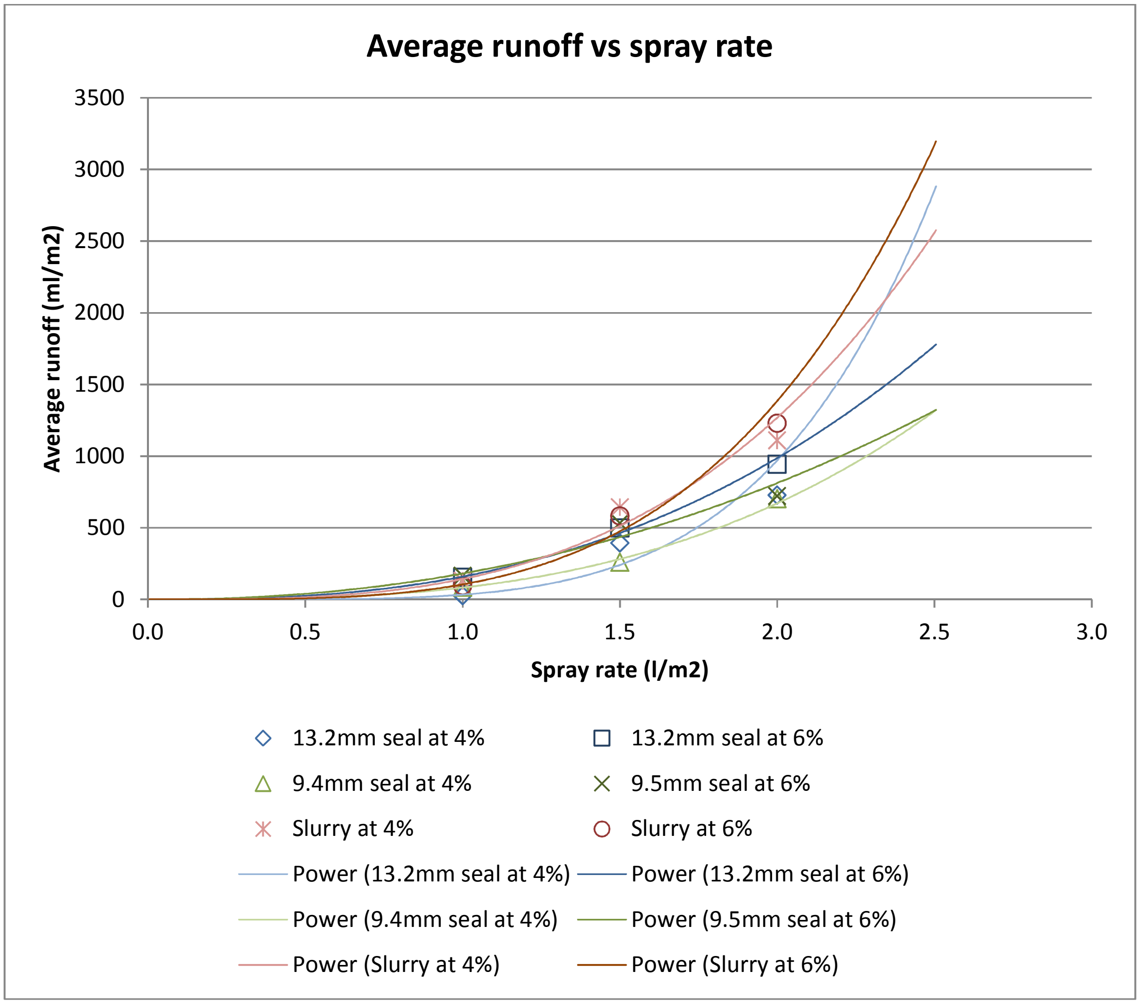


Figure 4. 5: Average runoff versus spray rate (combined Graph 2)

From observation and analysis, it can be seen that a nonlinear relationship exists between runoff and spray rate. These lines only indicate typical trends for tests done.

From extrapolation, Figure 4.5 shows that runoff would be zero at a spray rate of 0.5 ℓ/m^2. The gradient of the curves tends to steepen as the spray rate increases. The reason for this is that weight/film thickness of the binder is a function of spray rate and determines the energy possessed by the binder, i.e. the kinetic and potential energy ($0.5*m*v^2$ and mgh respectively. m = mass, v = velocity, g = gravitational force and h = height to the ground). The total energy increases as binder thickness increases. Binder film thickness also determines the rate at which the binder losses heat, i.e. thicker binders take a longer time to lose heat and hence to stop flowing. This substantiates the nonlinear relationship.

From Figure 4.5, it is possible to deduce the value beyond which flow yields, i.e. changes to excess. The aim is to minimise loss of the binder. Considering the steepest asymptotic curve

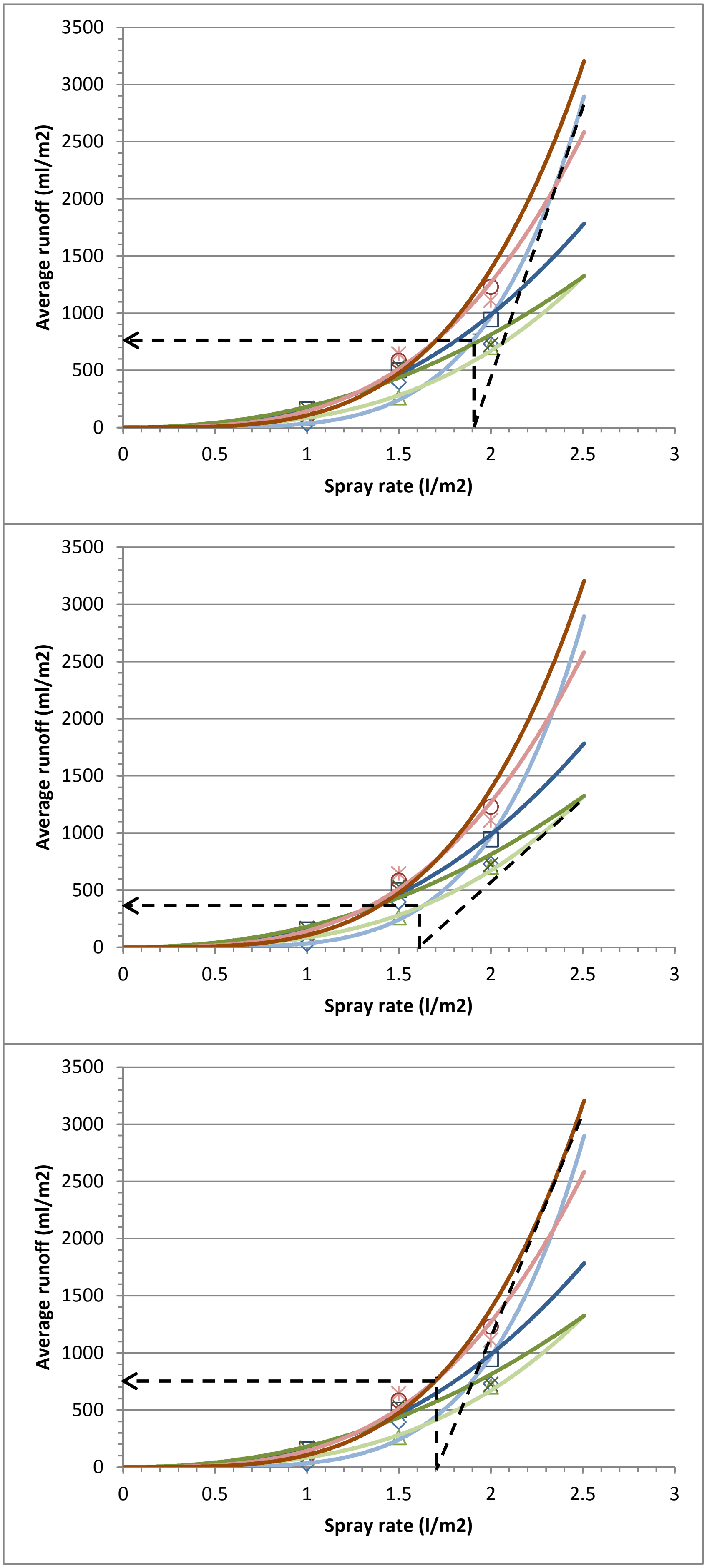


Figure 4. 6: Average runoff versus spray rate: yield values

for each of the three types of seals, the following values are obtained (see Figure 4.6 and Table 4.4 respectively). If the spray rate exceeds the amounts provided, a 65% spray grade emulsion should not be used as much more binder runoffs off the pavement.

Table 4. 4: Value before run-off starts to yield

Seal type	Runoff (mℓ/m^2)	Spray rate (mℓ/m^2)	Runoff (%)
13.2mm seal	750	1900	39.5
9.5mm seal	350	1600	21.9
Slurry seal	750	1700	44.1

4.3.2. Influence of gradient on runoff

Table 4.3 on page 117 was rearranged so that a plot of runoff versus gradient could be made (see Table 4.5 and Figure 4.7 on page 124). This was done by holding spray rate constant.

Considering Figure 4.7a, it can be seen that runoff increases with increase in gradient, except for three observations on the slurry seal at 6%. The problem could have arisen from removing the gutter a little earlier, as previously mentioned.

At a spray rate of 2 ℓ/m^2, a negligible increase in runoff for the 9.5mm seal is noted. Referring to Table 4.1 on page 110, the duration over which the emulsion was collected is adequate. This decrease might, therefore, have been caused by a decrease in mechanical efficiency of the spray bar.

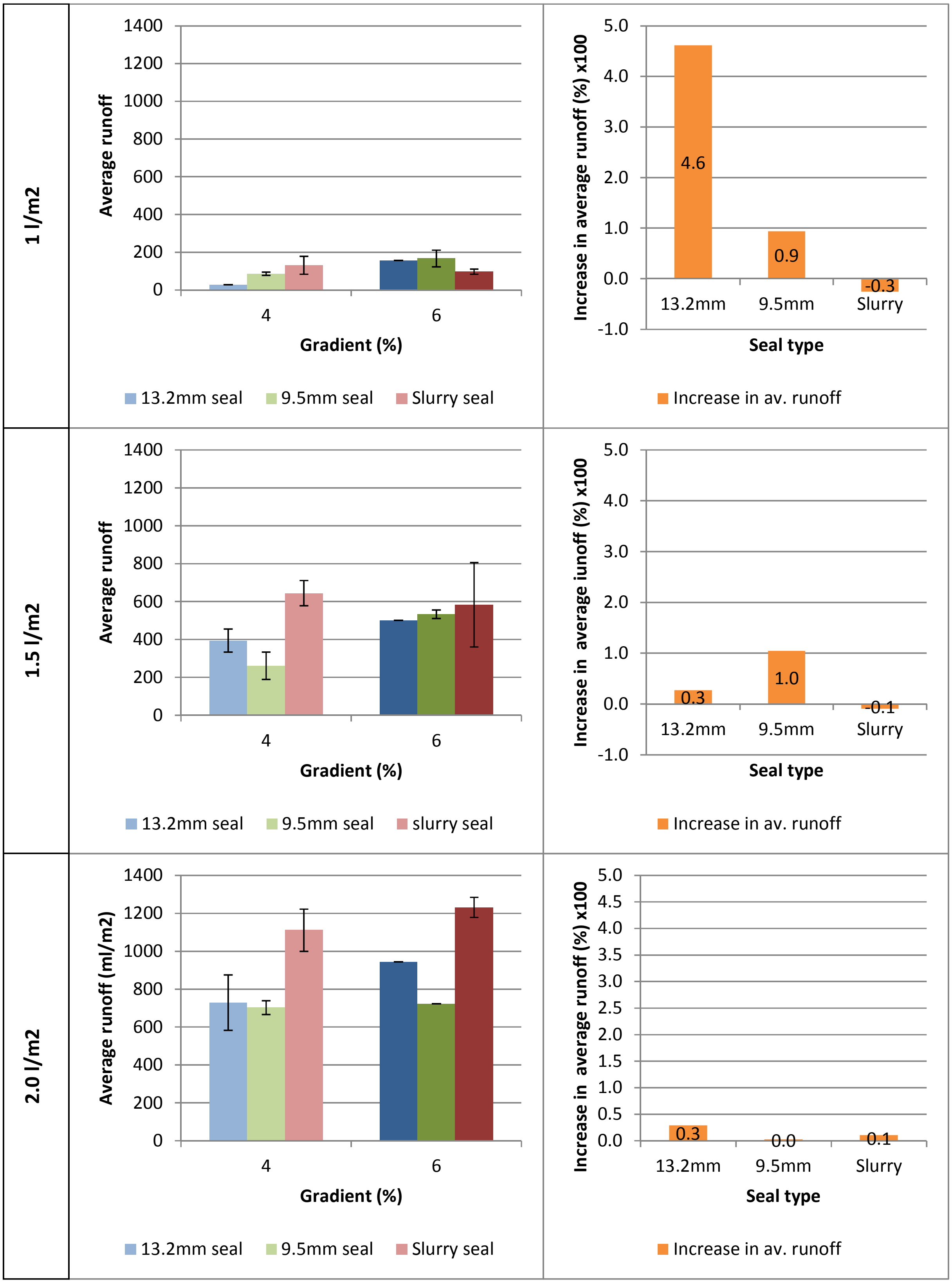
The increase in run-off due to increase in gradient is provided in Figure 4.7b.

A scatter plot of the combined data is provided in Figure 4.8. This figure has been drawn with arrows to indicate the behavioural aspect. By no means should this be read as a trend line (or function), but rather as an indication of behaviour. Green represents the runoff at 1 ℓ/m^2, blue represents 1.5 ℓ/m^2 and red 2 ℓ/m^2. Figure 4.8 shows that:

- At 1 ℓ/m^2, a decrease in gradient causes much less runoff whereas at 2 ℓ/m^2, a decrease in gradient does not cause much decrease in runoff. 1.5 ℓ/m^2 is intermediate;
- At 2 ℓ/m^2 and higher spray rates, there would still be some runoff at a gradient of 0%. This is because the binder film thickness is large and therefore the binder deforms under self-weight.

Table 4. 5: Data arrangement for gradient analysis

Surfacing seal	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m²)	Amount sprayed (mℓ)	Runoff reading 1 (mℓ/m²)	Runoff reading 2 (mℓ/m²)	Average runoff (mℓ/m²)	% Average runoff	Increase in % Average runoff (%) x100	Increase in average runoff (%) x100
13.2mm	1.6	4	1.0	1800	28	28	28	2.8		
13.2mm	1.6	6	1.0	1800		156	156	15.6	4.6	4.6
9.5mm	1.0	4	1.0	1800	78	94	86	8.6		
9.5mm	1.0	6	1.0	1800	211	122	167	16.7	0.9	0.9
Slurry	0.5	4	1.0	1800	178	83	131	13.1		
Slurry	0.5	6	1.0	1800	111	83	97	9.7	-0.3	-0.3
13.2mm	1.6	4	1.5	2700	333	456	394	26.3		
13.2mm	1.6	6	1.5	2700	500	500	500	33.3	0.3	0.3
9.5mm	1.0	4	1.5	2700	189	333	261	17.4		
9.5mm	1.0	6	1.5	2700	511	556	533	35.6	1.0	1.0
Slurry	0.5	4	1.5	2700	711	578	644	43.0		
Slurry	0.5	6	1.5	2700	361	806	583	38.9	-0.1	-0.1
13.2mm	1.6	4	2.0	3600	583	875	729	36.5		
13.2mm	1.6	6	2.0	3600		944	944	47.2	0.3	0.3
9.5mm	1.0	4	2.0	3600	667	739	703	35.1		
9.5mm	1.0	6	2.0	3600	722		722	36.1	0.0	0.0
Slurry	0.5	4	2.0	3600	1222	1000	1111	55.6		
Slurry	0.5	6	2.0	3600	1178	1283	1231	61.5	0.1	0.1



a) b)

Figure 4. 7: a) Average runoff versus gradient, b) Increase in average runoff due to increase in gradient

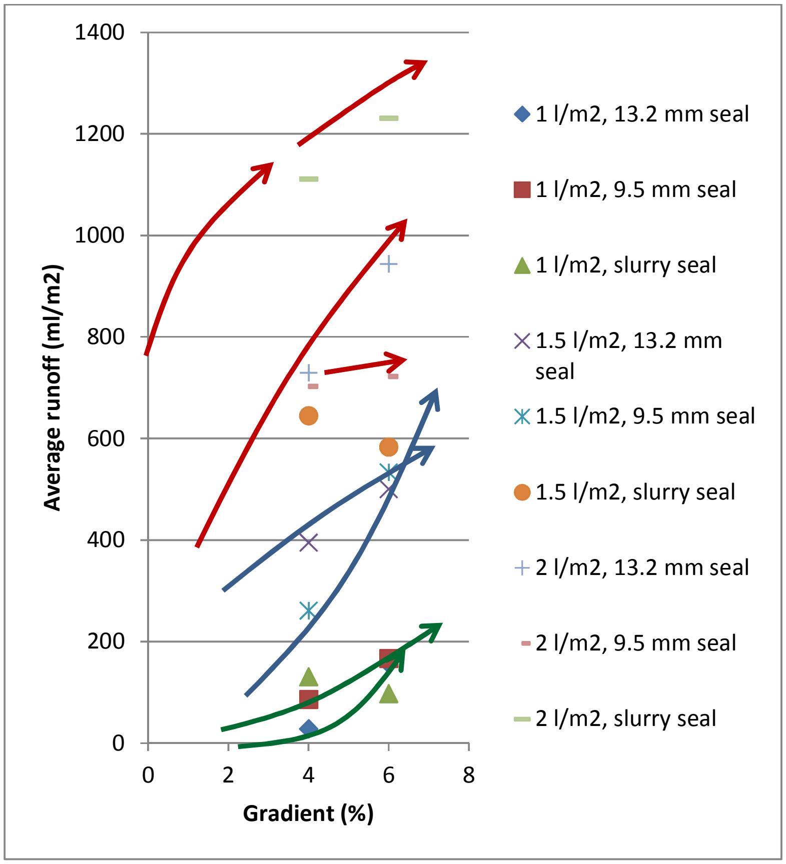


Figure 4. 8: Runoff versus gradient (combined data)

4.3.3. Influence of texture depth on runoff

The data in Table 4.3 on page 117 was again rearranged such that a plot of runoff versus texture depth could be made. Spray rate and gradient were held constant (see Table 4.6 on the next page and Figure 4.9 on page 127).

From Figure 4.9a, it can be seen that:

- A decrease in texture depth from 1.6 mm to 1.0 mm causes a slight decrease/negligible change in runoff (except for a spray rate of 1 ℓ/m^2 at a gradient of 4%).
- A decrease in texture depth from 1.0 mm to 0.5 mm causes an increase in runoff, except for 1 ℓ/m^2 at 6%, where this effect could not be highlighted. The outlier (1 ℓ/m^2) is explained by the reasons earlier stated, i.e., a decrease in mechanical efficiency of the spray bar and earlier removal of the gutter.
- The runoff from a texture depth of 0.5 mm is higher than the runoff from the 1.6 mm texture depth.

Table 4. 6: Data rearrangement for the texture depth versus runoff plot

Surfacing seal	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m^2)	Amount sprayed (mℓ)	Runoff reading 1 (mℓ/m^2)	Runoff reading 2 (mℓ/m^2)	Average runoff (mℓ/m^2)	% Average runoff	Increase in % Average runoff (%) x100	Increase in Average runoff (%) x100
13.2mm	1.6	4	1.0	1800	28	28	28	2.8		
9.5mm	1.0	4	1.0	1800	78	94	86	8.6	2.1	2.1
Slurry	0.5	4	1.0	1800	178	83	131	13.1	0.5	0.5
13.2mm	1.6	4	1.5	2700	333	456	394	26.3		
9.5mm	1.0	4	1.5	2700	189	333	261	17.4	-0.3	-0.3
Slurry	0.5	4	1.5	2700	711	578	644	43.0	1.5	1.5
13.2mm	1.6	4	2.0	3600	583	875	729	36.5		
9.5mm	1.0	4	2.0	3600	667	739	703	35.1	0.0	0.0
Slurry	0.5	4	2.0	3600	1222	1000	1111	55.6	0.6	0.6
13.2mm	1.6	6	1.0	1800		156	156	15.6		
9.5mm	1.0	6	1.0	1800	211	122	167	16.7	0.1	0.1
Slurry	0.5	6	1.0	1800	111	83	97	9.7	-0.4	-0.4
13.2mm	1.6	6	1.5	2700	500	500	500	33.3		
9.5mm	1.0	6	1.5	2700	511	556	533	35.6	0.1	0.1
Slurry	0.5	6	1.5	2700	361	806	583	38.9	0.1	0.1
13.2mm	1.6	6	2.0	3600		944	944	47.2		
9.5mm	1.0	6	2.0	3600	722		722	36.1	-0.2	-0.2
Slurry	0.5	6	2.0	3600	1178	1283	1231	61.5	0.7	0.7

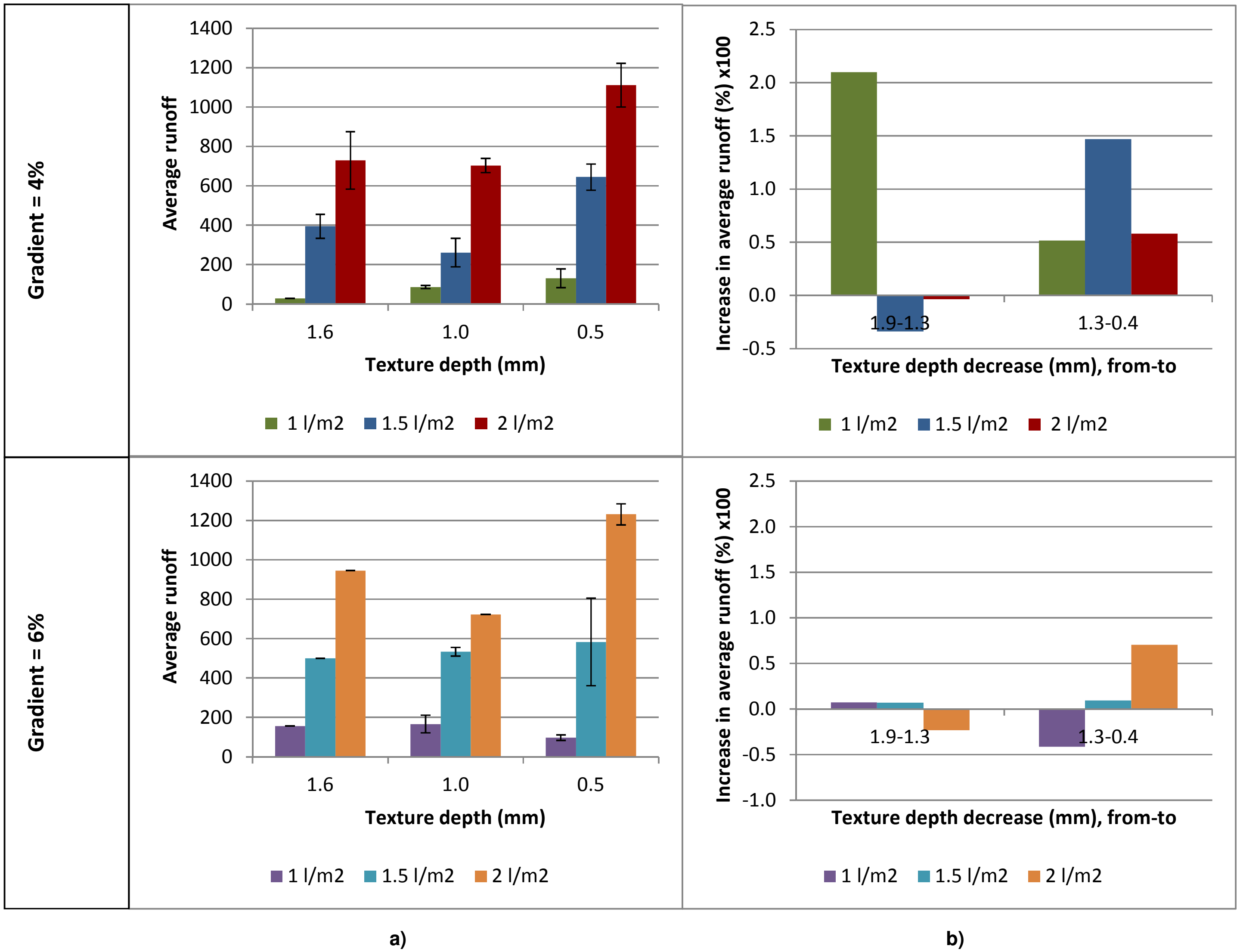


Figure 4. 9: Influence of texture depth on runoff: a) average runoff versus texture depth, and b) Increase in average runoff due to increase in texture depth

- Considering a gradient of 4% and a spray rate of 1.5 ℓ/m^2, a decrease in texture depth from 1.6 mm to 1.0 mm causes a 30% decrease in runoff. A decrease in texture depth from 1.0 mm to 0.5 mm causes a 150% increase in runoff (see Figure 4.9a and b).

The 9.5 mm seal (texture depth 1.0 mm) experiences less runoff than the 13.2 mm seal (texture depth 1.6 mm) because the 9.5mm seal has a higher density of protruding aggregates compared to the 13.2mm seal. When the binder is sprayed onto the seal surface, it flows following a path though the “valleys” created by the aggregate (see Figure 4.10 on the next page). As observed in the laboratory, the binder did not flow over the aggregate unless the latter was substantially embedded into the surface compared to the surrounding aggregate, which was rare. As the binder flows, the speed of the portion adjacent to the aggregate is much less than the speed of the portion far away from the aggregate (see 1 and 2 respectively in Figure 4.11). This was observed in other measurements concerning the velocity of the binder where paint was used to trace the motion of an element of the binder. When the paint got close to the aggregate it stopped flowing. Considering Figure 4.12 on page 130 concerning the kinematics of a fluid, it can be seen that the velocity adjacent the rigid surface is zero. As the distance H from the rigid surface becomes larger, a higher velocity is experienced at that distance. Since the aggregates in 9.5 mm seal are close to each other, the flowing binder is subjected to a larger area of rigid surface and hence a lower speed.

Also once the protruding aggregate is in the binder path, it inhibits or slows down the flow of the binder and the binder tends to build up behind the aggregate.

The combined data is also shown in Figure 4.13 on page 130. Red is for a gradient of 6% and Green for 4%. The least runoff is generally experienced with a texture depth of 1.0 mm. The general trend is that runoff is a decreasing function of texture depth.

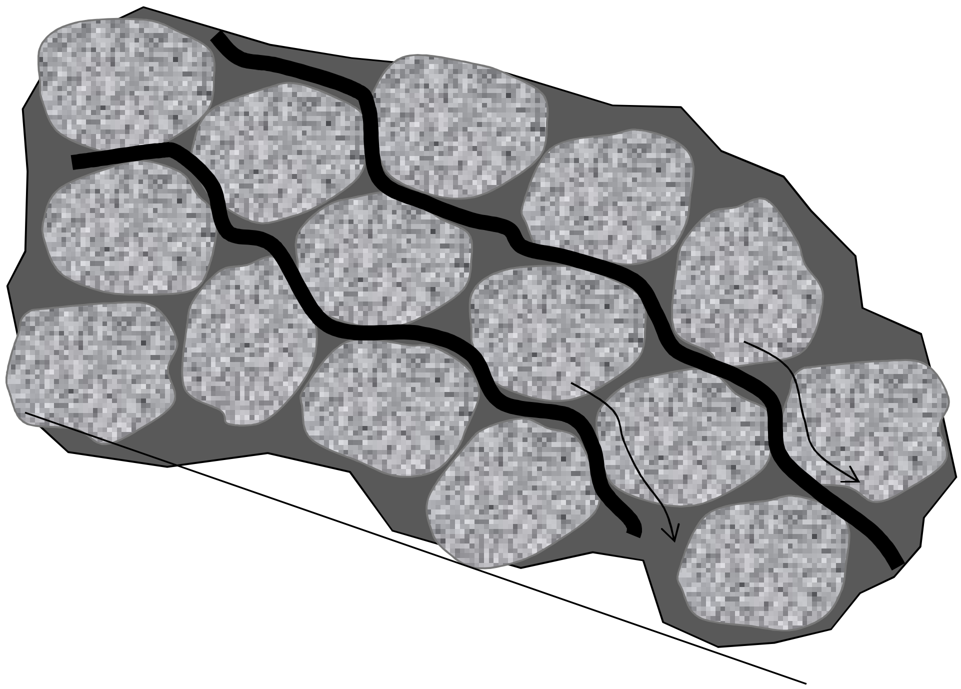


Figure 4. 10: Flow path of the binder for seals with large stone sizes (plan view)

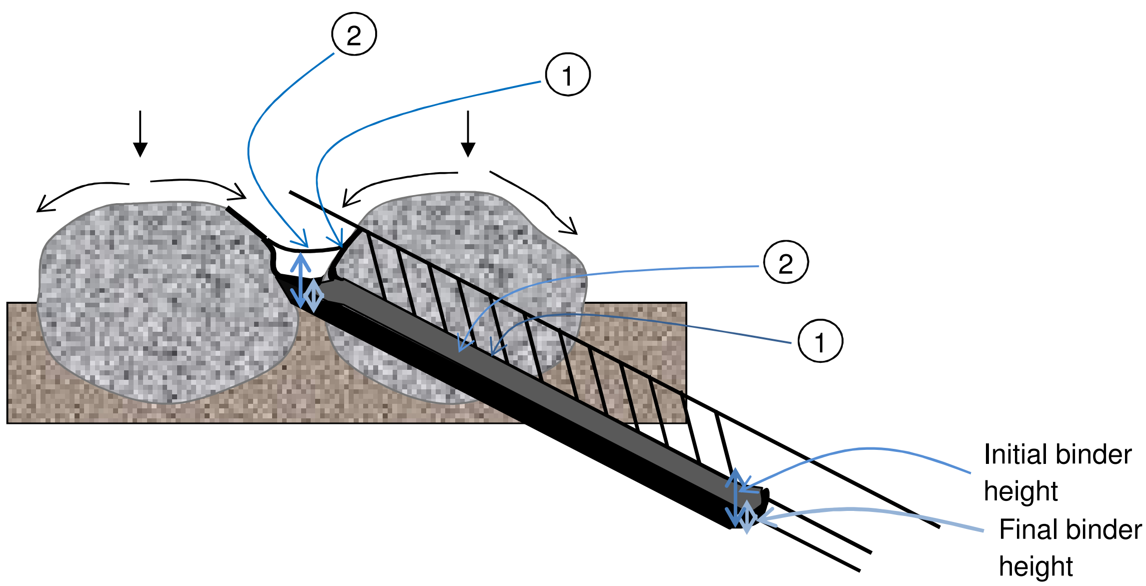


Figure 4. 11: Flow between the aggregates (cross-sectional view). (1) Low speed (2) High speed

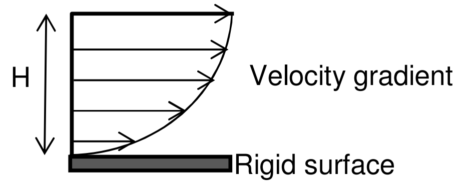


Figure 4. 12: Liquid flow over a rigid surface

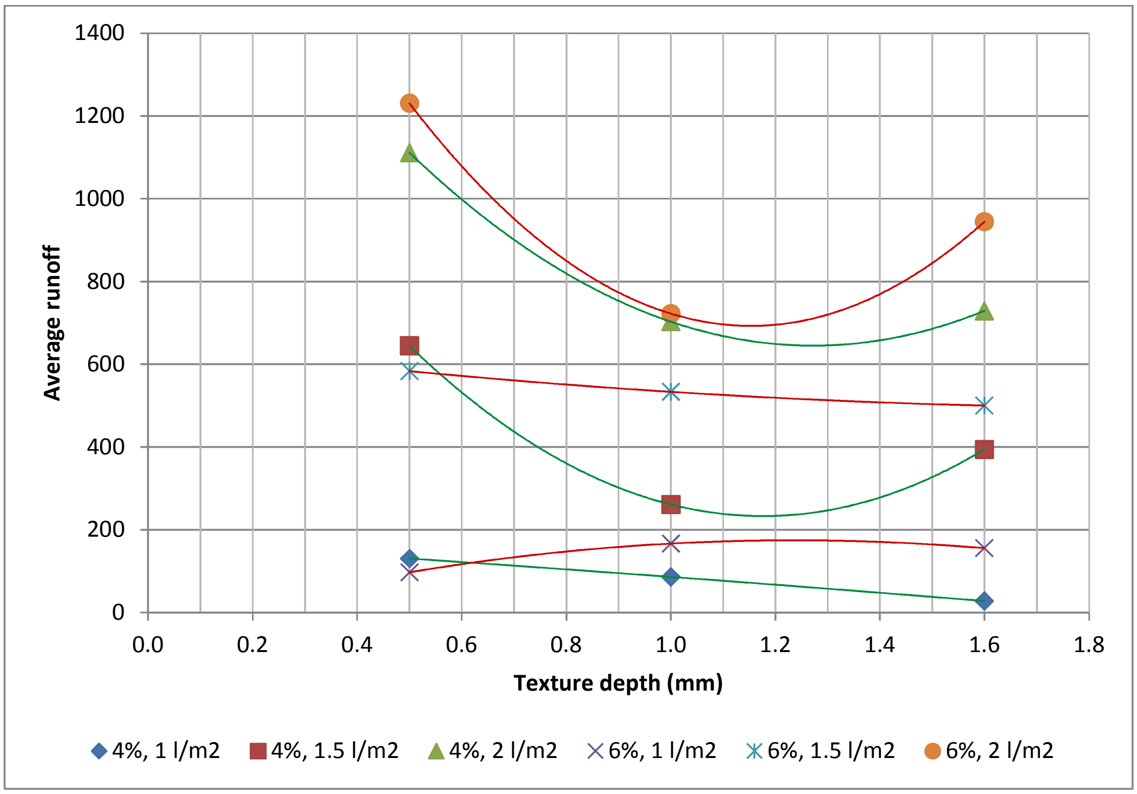


Figure 4. 13: Average runoff versus texture depth (combined data)

4.4. Analysing the combined influence of the three variables

The combined influence of spray rate, gradient and texture depth is evaluated in the proceeding section. Statistical analysis is used to portray the extent of the effect caused by each of these variables.

Data in Table 4.3 on page 117 was input into SPSS and the Linear Regression function used (Analyse, Regression, Linear). In order to understand how SPSS interpreted the input variables, the following types of variables are defined: They are represented by different symbols in the software.

i. Nominal variables: These allow for only qualitative classification. They cannot be ranked into an order. Examples include: red, blue and white, or male and female.
ii. Ordinal variables: These are nominal variables whose different states can be ordered into a meaningful sequence (UNESCO n.d.). Examples include: low, medium and high.
iii. Continuous variables: These are variables that not only allow ranking but also allow quantified comparison to be made between the variables. These variables can be measured on a linear or nonlinear scale (UNESCO n.d.)

It desired that the input variables are detected as continuous variables. The detected variables were fed into the dialogue box and the output generated is provided in Table 4.7.

Table 4. 7: Linear regression of runoff versus spray rate, gradient and texture depth: a) model summary, b) ANOVA, and c) coefficients

a) Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.923[a]	.853	.839	147.846

a. Predictors: (Constant), Tdepth, Grad, Sprate

b) ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4045502.934	3	1348500.978	61.692	.000[a]
	Residual	699473.371	32	21858.543		
	Total	4744976.306	35			

a. Predictors: (Constant), Tdepth, Grad, Sprate

b. Dependent Variable: Runoff

c) Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-771.949	164.893		-4.682	.000
	Sprate	795.917	60.358	.895	13.187	.000
	Grad	46.972	24.641	.129	1.906	.066
	Tdepth	-150.627	54.796	-.187	-2.749	.010

a. Dependent Variable: Runoff

This table is interpreted as follows:

Table 4.7a:

i. **R:** This is the correlation coefficient. It ranges from -1 to +1. +1 indicates a perfect positive correlation, -1 a perfect negative correlation and 0 no relationship. From the table, 0.923 indicates a very strong positive relationship between runoff and the three independent variables. This implies that when one or all of the independent variables change, runoff changes; and vice versa. For weak relationship, a change in one or all of the independent variables would cause a zero or negligible change in the dependent variable.

ii. **R-square:** R-square is derived from R. In a regression model with only one independent variable, it is the square of the correlation coefficient r (Princeton University 2007). R-square indicates how much of the dependent variable can be explained by the independent variable. From Table 4.7a, an R-square of 0.853 indicates that 85.3% of the variability of the runoff is accounted for the variables in the model. This R-squared is very high and therefore adequate.

iii. **Adjusted R-square:** This is used to determine the point at which the model would be best fit without unnecessary terms included. The adjusted R-square increases as the number of significant independent variables increases. It reaches a maximum and then starts decreasing as less significant variables are introduced into the model. The adjusted R-square can be negative, and its value is always be less than or equal to that of R-square. If the adjusted R-square is much lower than the R-square, it is an indication that the regression equation may be over-fitted to the data points (The

University of Texas at Austin 2010). From Table 4.7a, the adjusted R-square is 0.839 which is close to the R-square value of 0.853.The model is, therefore, not an over-fit.

iv. **Standard error of estimate (SEE):** As with the case of R and R-square, the standard error of estimate is a measure of variability or dispersion of predictions in a regression. For a simple linear regression, it is calculated as:

$SEE = \sqrt{\frac{SSE}{n-2}} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-2}}$, where

SSE = residual sum of squares

y_i = y-value of an offset point

$\hat{y}_i$ = y-value on the predicted line of best fit.

Note that when a population is used instead of a sample, the denominator is n rather than n-2. The reason as why n-2 is used rather than n-1, for the case of the sample, is that two parameters (slope and intercept) are estimated in order to estimate the sum of squares (Lane n.d.).

For a multiple regression, SEE for the sample calculated as: $SEE = \sqrt{\frac{SSE}{n-K-1}}$.

A low standard error of estimate implies that most of the observed values cluster fairly closely to the regression line. A large standard error of estimate, on the other hand, implies that most of the observed values are far away from the regression line (McHugh 2008).

From Table 4.7a, the standard error of estimate is 147.846. This implies that the standard deviation of the offsets to the predicted line is approximately 147.846 mℓ/m^2 (when considering one standard deviation off the predicted line in the vertical direction). Though the minimum standard error of estimate a predicted line can have is zero, the maximum is undefined.

Table 4.7b:

v. **Sum of squares**: As described in Section 4.2.2, the sum of squares indicates to the extent to which data points are dispersed. This is used to determine the function which best fits the data. 'In order to determine the sum of squares, the distance between each data point and the line of best fit is squared and then all of the squares are summed up. The line of best fit will minimize this value.' (Investopedia 2013). The regression sum of squares (SSR), residual sum of squares (SSE), total sum of squares (SST), the degrees of freedom, mean square, F-value and Sig. are computed as shown on Section 4.2.2.

vi. **F:** The F-statistic tests the overall significance of the model. (Note: that this says nothing about the magnitude of the independent variables on the dependent variable. This will be further explained in the subsequent discussions). The F-statistic determines whether all the independent variables in the regression have a relationship with the dependent variable. The null hypothesis tested is that there is no relationship and this is written as:

H_0: B1 = B2 = … = 0. The alternate hypothesis is that at least one of the B's (coefficients) is not zero. Rejecting the null hypothesis implies that all the independent variables as a group are related to the dependent variable (Parker 2008). The probability that the F-value is equal to 61.692 (as read from Table 4.7b) is the p-value and is provided under the Sig. column. Since the p-value is 0.000, which is less than the level of significance α = 0.05, the null hypothesis is rejected (The University of Texas at Austin 2010). The relationship between the F statistic and the p-value is illustrated in Figure 4.14 below. The F-critical is derived from tables using the degrees of freedom of the regression and degrees of freedom of the residuals. With software, there is no need to determine F-critical, as the p-value can be compared with the chosen level of significance, α.

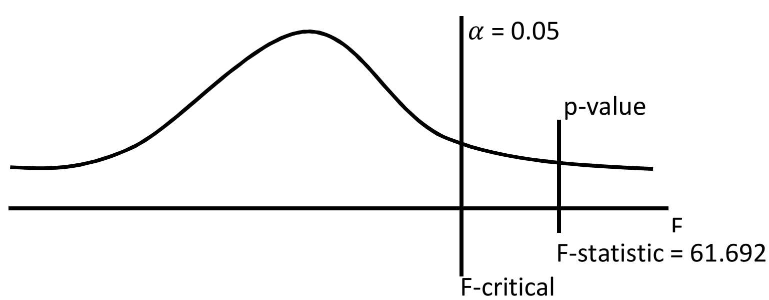


Figure 4. 14: The probability distribution of the F-statistic

The p-value is also called the significance. An outcome is said to be statistically significant if it is unlikely to have occurred by chance. In other words, if it is very certain that the statistic is reliable, then it is statistically significant (StatPac Inc 2013). If the p-value is greater than the level of significance α, the model is a poor fit for the data (University of Colorado, n.d). α = 0.05 is the most commonly used and is what was used in this analysis.

As F is computed from mean sum of regression divided by the mean sum of residual, the larger the F-value is, the more in the direction of significance.

Table 4.7c

vii. **Unstandardized coefficients, B:** This provides the coefficients of the independent variables. These are referred to as the unstandardized coefficients because they are measured in their natural units. Hence, these coefficients cannot be compared with one another to determine which one has the most influence on the dependent variable because they can be measured on different scales (University of Windsor n.d.). To determine this influence, on looks at the standardised Beta (Note: that you could use typical industrial values and incorporate them into your regression with unstandardized coefficients and hence do a sensitivity analysis in order to establish which one might have the largest influence on your dependent variable.)

viii. **Standardised coefficients, Beta:** These are the coefficients one would obtain if all the dependent and independent variables are standardised before running the regression. Standardising the variables puts all of these variables on the same scale. The magnitude of the coefficients can then be compared to determine which one has more effect (University of Windsor n.d.). The larger betas are associated with the larger t-values.

ix. **The t-statistic:** This test is performed on each independent variable to make sure that each variable on its own has a relationship with the dependent variable (Parker 2008). The null hypothesis that there is no relationship is rejected if the p-value is less than α. The t-statistic in software output (Table 4.7c) is obtained by dividing the unstandardized coefficient of a variable by its standard error (Princeton University 2007). The variable with a higher t statistic is the most influential.

x. **Sig. column:** The Sig. column in Table 4.7c provides the p-value of each of the independent variables. For this case, the p-value corresponds to the t-statistic (t-distribution).

xi. **Standard error:** The standard error of the unstandardized coefficient gives the dispersion of the data point points of that particular independent variable.

The model for the unstandardized coefficients is provided below:

Runoff = -771.949 + 795.917(spray rate) + 46.972(gradient) - 150.627(texture depth).

What this equation is saying is that if spray rate goes up by one unit, holding gradient and texture depth constant, runoff will go up by 795.917 units. If gradient goes up by 1 unit, holding spray rate and texture depth constant, runoff will go up by 46.972 units. If texture depth goes up by one unit, holding spray rate and gradient constant, runoff decreases by 150.627 units. The regression also predicts that if spray rate, gradient and texture depth are all equal to zero, the runoff would be -771.949 units. Physically, this is not possible. Note that this linear model does not cross the axes at the origin but at some positive value on the independent variable axes, thus intercepting the y-axis (runoff axis) at -771.949 units. This means that zero runoff will be experienced before the spray rate, gradient and texture depth get to zero.

The p-value of spray rate and texture depth is under the expected significance level of 0.05 which means that the author can with confidence reject the null hypothesis which states that there is no relationship between spray and runoff or texture depth and runoff. This implies that each of these two variables have a 95% probability that they have an effect on the runoff result. The reader should be aware that although texture depth is significant and spray rate even more significant, the Sig. (or p-value) used to represent this has no connection to the magnitude by which runoff would change as this is done by the standardised coefficients or the t-statistic. The Sig. (or p-value) only says something about the assurance of that effect and nothing about the magnitude of the effect.

Consequently it can be seen that gradient does not fall within the 95% confidence interval. However, it is very close and does fall within the 90% confidence. Although it falls outside the expected 95% confidence interval, it is of the author's opinion that all three of these variables can be accepted as having a significance on runoff. Hence, comparing the t-statistics (which is connected to the standardised coefficients) of the variables, it is shown that spray rate has the most influence on runoff, followed by texture depth, followed by gradient.

It was earlier noted that the overall model is significant as indicated by the p-value in Table 4.7b. It is important to note that it is possible to have a model with global significance but with insignificant independent variables. Although these variables may be insignificant in isolation, their interaction generates a significant model. It is also possible to have significant independent variables whose interaction yields an insignificant model. The latter model would be of no importance. It is important that at least the overall significance is less α.

Table 4.8 on the next page was used as a cross-reference to confirm the output in Table 4.7. This table was generated using the Linear Regression function of Ms Excel.

Table 4. 8: Excel regression output for the combined influence of spray rate, gradient and texture depth

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.923356
R Square	0.852587
Adjusted R Square	0.838767
Standard Error	147.8463
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	4045503	1348501	61.69217	2.13129E-13
Residual	32	699473.4	21858.54		
Total	35	4744976			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-771.949	164.8931	-4.68151	5E-05	-1107.82526	-436.073
Tdepth	-150.627	54.7955	-2.7489	0.009747	-262.242075	-39.0125
Grad	46.97222	24.64106	1.906258	0.065632	-3.219970491	97.16441
Sprate	795.9167	60.35802	13.18659	1.76E-14	672.9714054	918.8619

Table 4.8 provides similar output to that of SPSS. The interpretation of the output is the same as already described. The Significant F is the p-value of the overall model. The Lower 95% and Upper 95% represent lower and upper confidence intervals. For example, there is 95% confidence that the actual Tdepth coefficient lies between -262.24 and -39.01.

The influence of each of the three independent variables was also determined by holding two independent variables constant and varying the third. The results are shown in Tables 4.9 to 4.11. Note that A refers 13.2mm seal, B to 9.5mm seal and C to the slurry seal.

From these tables it can be observed that the spray rate has the largest influence on the magnitude of the runoff followed by texture depth which has the same magnitude of effect. According to these tables the gradient has a significant smaller effect.

When comparing this to the standardised coefficients in Table 4.7 which can also show the contribution of magnitude of each of the independent variables, the sequence of the magnitudes i.e spray rate being highest and gradient being the smallest is the same. However, these standardised coefficients show that the texture depth’s magnitude of effect on runoff is closer to that of the gradient.

Table 4. 9: Influence of spray rate: Holding texture depth and gradient constant

Surfacing	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m²)	Average runoff (m ℓ/m²)	Difference in average runoff (m ℓ/m²)
A	1.6	4.0	1.0	28.0	
A	1.6	4.0	1.5	394.5	
A	1.6	4.0	2.0	729.0	334.5
A	1.6	6.0	1.0	156.0	
A	1.6	6.0	1.5	500.0	
A	1.6	6.0	2.0	944.0	444.0
B	1.0	4.0	1.0	86.0	
B	1.0	4.0	1.5	261.0	
B	1.0	4.0	2.0	703.0	442.0
B	1.0	6.0	1.0	166.5	
B	1.0	6.0	1.5	533.5	
B	1.0	6.0	2.0	722.0	188.5
C	0.5	4.0	1.0	130.5	
C	0.5	4.0	1.5	644.5	
C	0.5	4.0	2.0	1111.0	466.5
C	0.5	6.0	1.0	97.0	
C	0.5	6.0	1.5	583.5	
C	0.5	6.0	2.0	1230.5	647.0
Average of difference:					**375.1**

Table 4. 10: Influence of gradient: Holding texture depth and spray rate constant

Surfacing	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m²)	Average runoff (m ℓ/m²)	Difference in average runoff (m ℓ/m²)
A	1.6	4.0	1.0	28.0	
A	1.6	6.0	1.0	156.0	128.0
A	1.6	4.0	1.5	394.5	
A	1.6	6.0	1.5	500.0	105.5
A	1.6	4.0	2.0	729.0	
A	1.6	6.0	2.0	944.0	215.0
B	1.0	4.0	1.0	86.0	
B	1.0	6.0	1.0	166.5	80.5
B	1.0	4.0	1.5	261.0	
B	1.0	6.0	1.5	533.5	272.5
B	1.0	4.0	2.0	703.0	
B	1.0	6.0	2.0	722.0	19.0
C	0.5	4.0	1.0	130.5	
C	0.5	6.0	1.0	97.0	-33.5
C	0.5	4.0	1.5	644.5	
C	0.5	6.0	1.5	583.5	-61.0
C	0.5	4.0	2.0	1111.0	
C	0.5	6.0	2.0	1230.5	119.5
Average of difference:				**134.3**	

Table 4. 11: Influence of texture depth: Holding gradient and spray rate constant

Surfacing	Texture depth (mm)	Gradient (%)	Spray rate (ℓ/m²)	Average runoff (mℓ/m²)	Difference in average runoff (mℓ/m²)
A	1.6	4.0	1.0	28.0	
B	1.0	4.0	1.0	86.0	58.0
C	0.5	4.0	1.0	130.5	44.5
A	1.6	4.0	1.5	394.5	
B	1.0	4.0	1.5	261.0	-133.5
C	0.5	4.0	1.5	644.5	383.5
A	1.6	4.0	2.0	729.0	
B	1.0	4.0	2.0	703.0	-26.0
C	0.5	4.0	2.0	1111.0	408.0
A	1.6	6.0	1.0	156.0	
B	1.0	6.0	1.0	166.5	10.5
C	0.5	6.0	1.0	97.0	-69.5
A	1.6	6.0	1.5	500.0	
B	1.0	6.0	1.5	533.5	33.5
C	0.5	6.0	1.5	583.5	50.0
A	1.6	6.0	2.0	944.0	
B	1.0	6.0	2.0	722.0	-222.0
C	0.5	6.0	2.0	1230.5	508.5

Average of difference: -11.5 and 336.125 (for a texture depth decrease from 1.6 to 1.0mm and from 1.0 to 0.5mm respectively).

The reason for this difference could be attributed to the negative values (as calculated in the difference in average runoff for some cases) as reported in the calculations in Table 4.11.

From these results and discussion, conclusions were made in Section 4.5.

4.5. Conclusion

From the analysis presented in the preceding sections of this chapter, it is shown that:

- As spray rate increases, a larger amount of runoff is expected.
- The yield value above which excess flow occurs was determined. This was a spray rate of 1.9 ℓ/m^2 (corresponding to 750 $m\ell/m^2$) for the 13.2mm seal, 1.6 ℓ/m^2 (corresponding to 350 $m\ell/m^2$) for the 9.5mm seal and 1.7 ℓ/m^2 (corresponding to 750 $m\ell/m^2$) for the slurry seal;
- Runoff occurs within a duration of 10 minutes. 10 minutes is approximately the average time it took for the emulsion to stop flowing, irrespective of texture depth, gradient and spray rate. Given that the binder runs off in the first few minutes, 10 minutes is long enough (worst case scenario) before the aggregate can be applied. Though the longest time the aggregate spreader lags behind the bitumen distributor is approximately 15-20 minutes (Louw 2012), the emulsion would have stopped flowing by this time. The only concern would be breaking of the emulsion;
- Though the sand patch test would produce a larger patch diameter for seals with a lower macro-texture, for the same volume of sand, once the aggregate size is beyond a certain limit, the binder flows between the aggregates rather than over the aggregates. The higher the aggregate density of these larger aggregates, the more the binder is trapped. This explains the reason why the 9.5mm seal is more favourable than the 13.2mm seal; and
- The combined influence of the three variables was described using a regression model. By evaluating the model, it could be seen that spray rate had the highest effect on the magnitude of runoff, with texture depth and gradient having lower effects of magnitudes.

Chapter 5 : Conclusions and recommendations

This study looked at the run-off behaviour of bitumen emulsions. With reference to the various chapters in this document, the following conclusions are made:

5.1. Literature review

Bitumen emulsion is a material with rheological properties. A literature review was conducted to study the factors that influence the rheological performance of the emulsion, not only with respect to run-off but also with the related construction properties. Putting more emphasis on the two most related properties, that is, sprayability and run-off, the most recent literature showed that the best way to measure sprayability and run-off was by using the 3-Step Shear Test. Also from literature it was found that the shear rate for surface run-off ranges from 0.1 to 10 s^{-1}, though the elevation was not specified. The shear rate of the emulsion used in the test was variable but lay within the stated range. This shear rate is not discussed in Chapter 4 because it was affected by a number of factors, among which include:

- The binder was subjected to variable shear stress as this stress is dependent on a combination of binder thickness, gradient and macro-texture. The combination varied from one test to the next. A comparison would only be appropriate between test repeats and the experiment had only one repeat.
- Binder thickness measurements were influenced by the macro-texture of the seal. This macro-texture determined the extent to which the binder would build up before it started flowing. Though the highest runoff is expected with the slurry seal, this seal would have a low initial velocity because it does not have protruding aggregate to contain the emulsion as the initial film thickness builds up. The comparison of shear rate between seal types was, therefore, found to be inappropriate.
- Flow was unsteady and therefore controlling the time at which the binder thickness was measured and the paint drop placed need stringent monitoring. Strict control over this time was not possible in the laboratory because the time between stopping and reversing the conveyor varied. The emulsion from the nozzles had to first stop dripping considerably and the time it took to do this varied depending on spray rate. Reversing was necessary because the conveyor was hanging over the spray surface (an issue of space constraint).

5.2. Methodology

Samples of three types of surfacing seals were constructed. The texture depth of these seals was adjusted to representative values found in the field. Spray tests (using cationic spray grade 65%) were then performed on these seals, at various spray rates and gradients. The spray rates were selected based on critical values recommended for the particular seals. In order to make a systematic comparison, the selected spray rates were applied to all the three seal types. Various gradients were also considered.

5.3. Results and findings

From the analysis of data obtained, the following findings are presented:

5.3.1. Influence of spray rate on runoff

It was found that:

- Runoff increases with increase in spray rate, as expected;
- The runoff at a gradient of 6% is higher than the runoff at 4%;
- Adsorption of the binder onto the seal surface influences runoff;
- Zero runoff would be experienced at a spray rate of 0.5 ℓ/m^2 due to adsorption;
- By considering the gradient that had the steepest asymptotic curve, the yield value above which excess runoff occurs was determined. This was a spray rate of 1.9 ℓ/m^2 (corresponding to a runoff of 750 $m\ell/m^2$) for the 13.2mm seal, 1.6 ℓ/m^2 (corresponding to 350 $m\ell/m^2$) for the 9.5mm seal and 1.7 ℓ/m^2 (corresponding to 750 $m\ell/m^2$) for the slurry seal. Beyond these spray rates, a significant amount of binder is lost; and
- The lost binder at these spray rates could be remedied by placing a cover spray equivalent to the lost percentage. The benefit of this or using a more viscous binder would have to be evaluated.

5.3.2. Influence of gradient on runoff

- Runoff increases with increase in gradient as expected; and
- Gradient has limited influence on runoff when the spray rate is above 2 ℓ/m^2 because the binder thickness would be large. The binder would flow mainly as a result of self-weight.

5.3.3. Influence of texture depth on runoff

- A decrease in texture depth from 1.6 mm to 1.0 mm causes a slight decrease/negligible change in runoff whereas a decrease in texture depth from 1.0

mm to 0.5 mm causes a notable increase in runoff. This finding was attributed to the fact that the 9.5 mm seal (texture depth of 1.0 mm) had a higher density of aggregate compared to the 13.2 mm seal (texture depth 1.6 mm). The runoff from the slurry seal (texture depth 0.4 mm) was higher than that for the 13.2 mm seal, as expected.

5.3.4. General conclusions

- The general model obtained was:
  Runoff = -771.949 + 795.917(spray rate) + 46(gradient) - 150.627(texture depth).
  The t statistics showed that spray rate has the most influence on runoff, followed by texture depth, followed by gradient.
- It was noted that the speed of runoff decreases with time (unsteady flow) until when the emulsion stops dripping. It was also observed that the emulsion stopped flowing earlier at the upstream side than downstream. This implies that whereas there would be ravelling potential upstream, there would be a bleeding potential downstream or close to the side drains.

5.4. Implications of this research on construction practice

As mentioned in the Chapter 1, spray rate, gradient and texture depth are fixed construction conditions. The design spray rate is, however, chosen taking into consideration the factors mentioned in Chapter 3, among which is traffic, gradient, existing texture depth and the average least dimension of the aggregate that will be placed on top of the binder. This does not guarantee that runoff will not be experienced and therefore the obtained spray rate is cross-checked with the recommended maximum spray rate to prevent run-off. If the obtained spray rate exceeds the maximum recommended, another type of binder is chosen. Polymer modified and rubber modified binders have a higher maximum recommended spray rate limit and are therefore more suitable to prevent run-off. This research helps one determine how much binder would be lost with the less viscous binder. Provision may be made to compensate for this by applying a cover spray in amounts of the lost binder. The costs involved would be evaluated to determine whether compensation is a better option than a single application using a more viscous binder.

5.5. Recommendations

- Since the number of test repeats used in the analysis was small, the results produced are only first order estimates/indications. It is therefore recommended that the number be increased to approximately eight repeats per setup for a good limit of accuracy/reliability. The sample size should also be increased. For example for spray rate, the number of spray rates should be increased to incorporate a spray rate of 0.5 ℓ/m^2; to better evaluate the effect of adsorption.

- It is also recommended that runoff is collected after a certain interval of time, say after every three minutes. This will enable determining/confirming the time interval within which most of the binder runs off, and hence would be the time interval/duration that would be used in RV testing for run-off. Beyond that duration, the binder shear properties on the pavement would have changed.
- Future tests should be conducted at the maximum recommended field temperature to prevent run-off, i.e. within the sealing seasons. This was not possible in the current study because the heating equipment was not available; and
- RV testing should be performed to analyse the shear rates specific to the different factors experienced in the field.

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